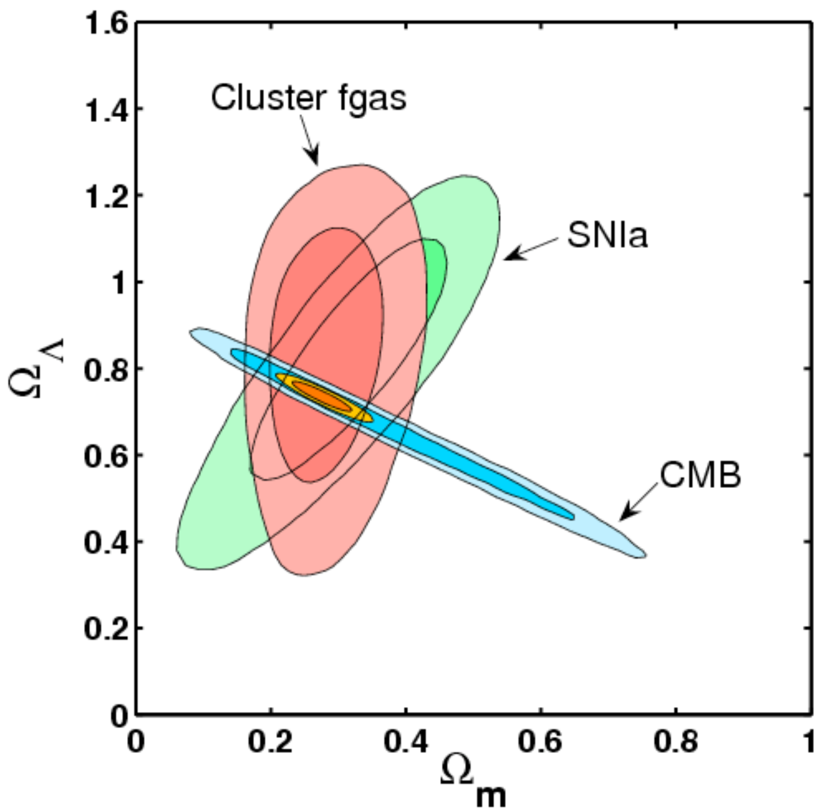
X-ray clusters and cosmology

Steve Allen, KIPAC

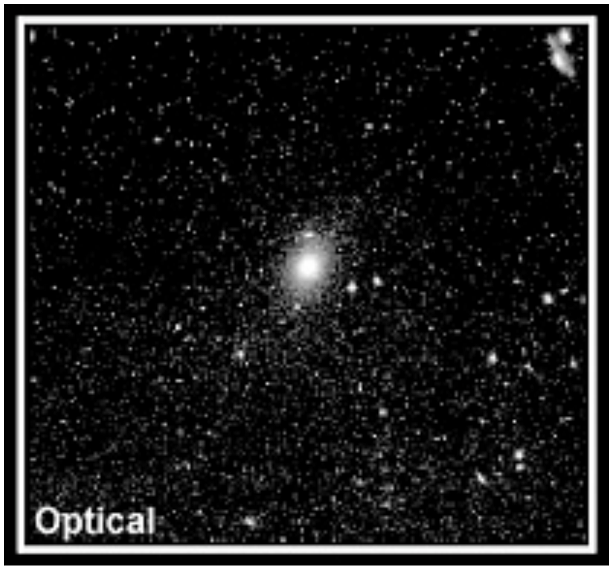


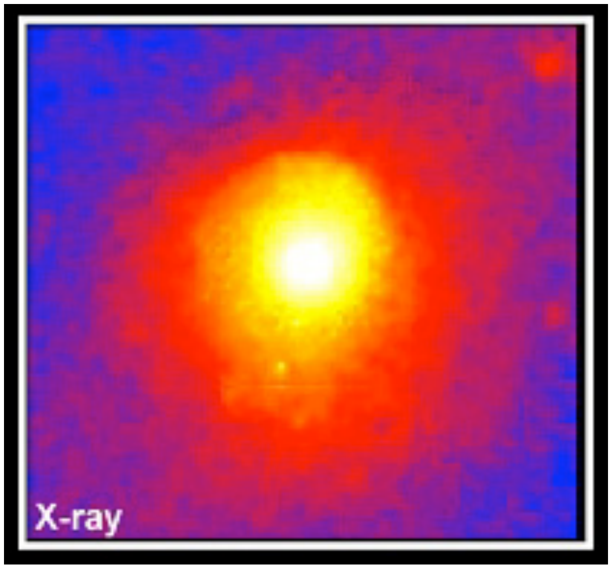
In collaboration with:

David Rapetti (KIPAC)
Adam Mantz (KIPAC)
Harald Ebeling (Hawaii)
Robert Schmidt (Heidelberg)
R. Glenn Morris (KIPAC)
Andy Fabian (Cambridge)

Why study clusters at X-ray wavelengths?

Most baryons in clusters (like Universe) are in form of gas, not stars (6x more).
In clusters, gravity squeezes gas, heating it to X-ray temperatures (10^7-10^8 K)





Since clusters only shine in X-rays if they really are massive, X-ray observations produce remarkably clean cluster catalogues, vital for cosmology.

Primary X-ray observables (density, temperature) relate directly to total (dark plus luminous) mass in a way that's well understood (hydrostatic equilibrium) and can be well modelled by hydro. simulations.

Outline of the talk

1) Constraints on the mean matter density Ω_m and dark energy (Ω_{de},w) from measurements of the baryonic mass fraction in the largest dynamically relaxed clusters [distance measurements].

2) Constraints on the mean matter density Ω_m, the amplitude of matter fluctuations σ_8, and dark energy (Ω_{de},w), from the evolution of the number density of X-ray luminous clusters [growth of cosmic structure].

+ a little on what these tests can do in combination.

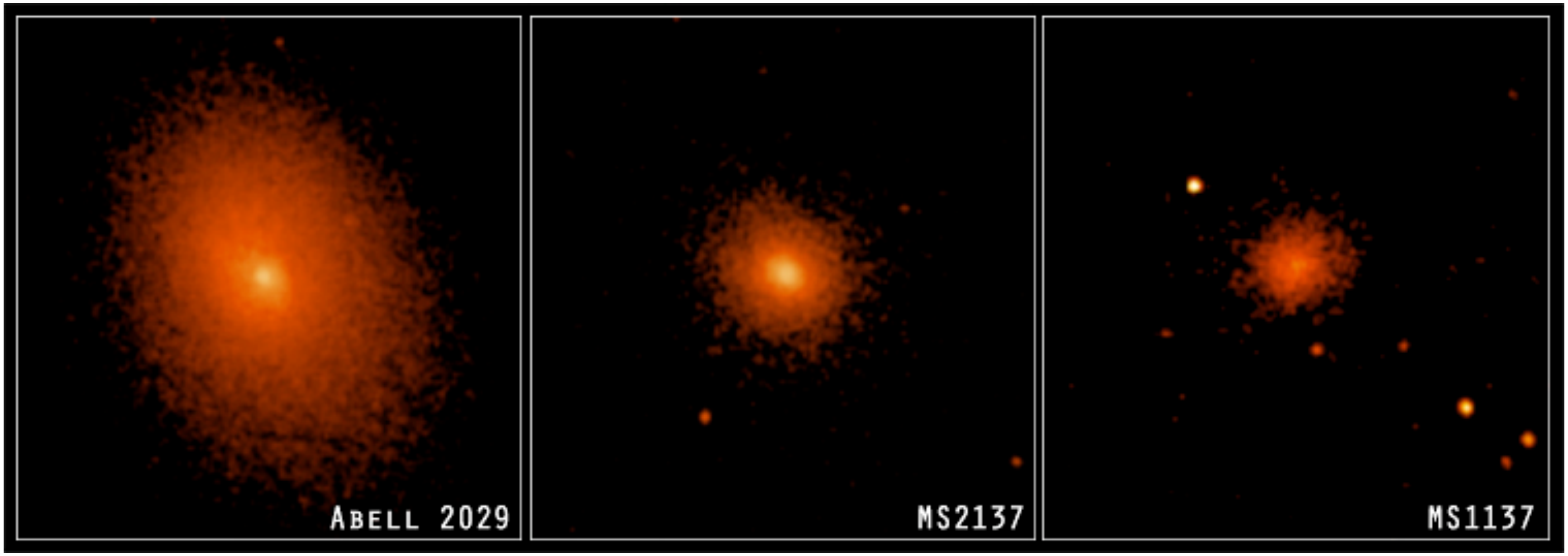
Probing cosmology with X-ray clusters

1. The fgas experiment

Allen et al. 2008, MNRAS, 383, 879

(See also White & Frenk ’91; Fabian ’91; Briel et al. ’92; White et al ’93; David et al. ’95; White & Fabian ’95; Evrard ’97; Mohr et al ’99; Ettori & Fabian ’99; Roussel et al. ’00; Grego et al ’00; Ettori et al. ’03; Sanderson et al. ’03; Lin et al. ’03; LaRoque et al. ’06; Allen et al. ’02, ’03, ’04.)

The Chandra data



42 hot ($kT>5keV$), highly X-ray luminous ($L_X>10^{45}\,h_{70}^{-2}$ erg/s), dynamically relaxed clusters spanning redshifts $0<z<1.1$ (lookback time of 8Gyr)

Regular X-ray morphology: sharp central X-ray surface brightness peak, minimal X-ray isophote centroid variation, low power-ratios (morphological selection).

Constraining Ω_m with f_{gas} measurements

BASIC IDEA (White & Frenk 1991): Galaxy clusters are so large that their matter content should provide a fair sample of matter content of Universe.

For relaxed clusters: X-ray data → good total mass measurements
→ precise X-ray gas mass measurements

If we define:

$$f_{gas} = \frac{\text{X-ray gas mass}}{\text{total cluster mass}} \qquad s = f_{star}/f_{gas} \sim 0.16$$

eg Lin & Mohr 04
Fukugita et al '98

Then:

$$f_{baryon} = f_{star} + f_{gas} = f_{gas}(1+s)$$

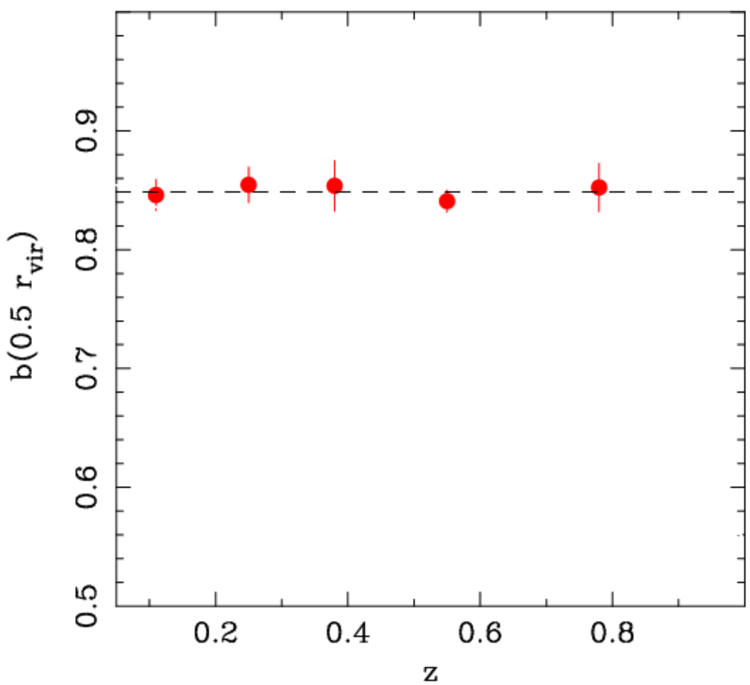
Since clusters provide ~ fair sample of Universe $f_{baryon} = b\Omega_b/\Omega_m$

$$\Omega_m = \frac{b\Omega_b}{f_{baryon}} = \frac{b\Omega_b}{f_{gas}(1+s)}$$

Constraining dark energy with f_{gas} measurements

The measured f_{gas} values depend upon assumed distances to clusters $f_{gas} \propto d^{1.5}$. This introduces apparent systematic variations in $f_{gas}(z)$ depending on differences between reference cosmology and true cosmology.

What do we expect to observe?



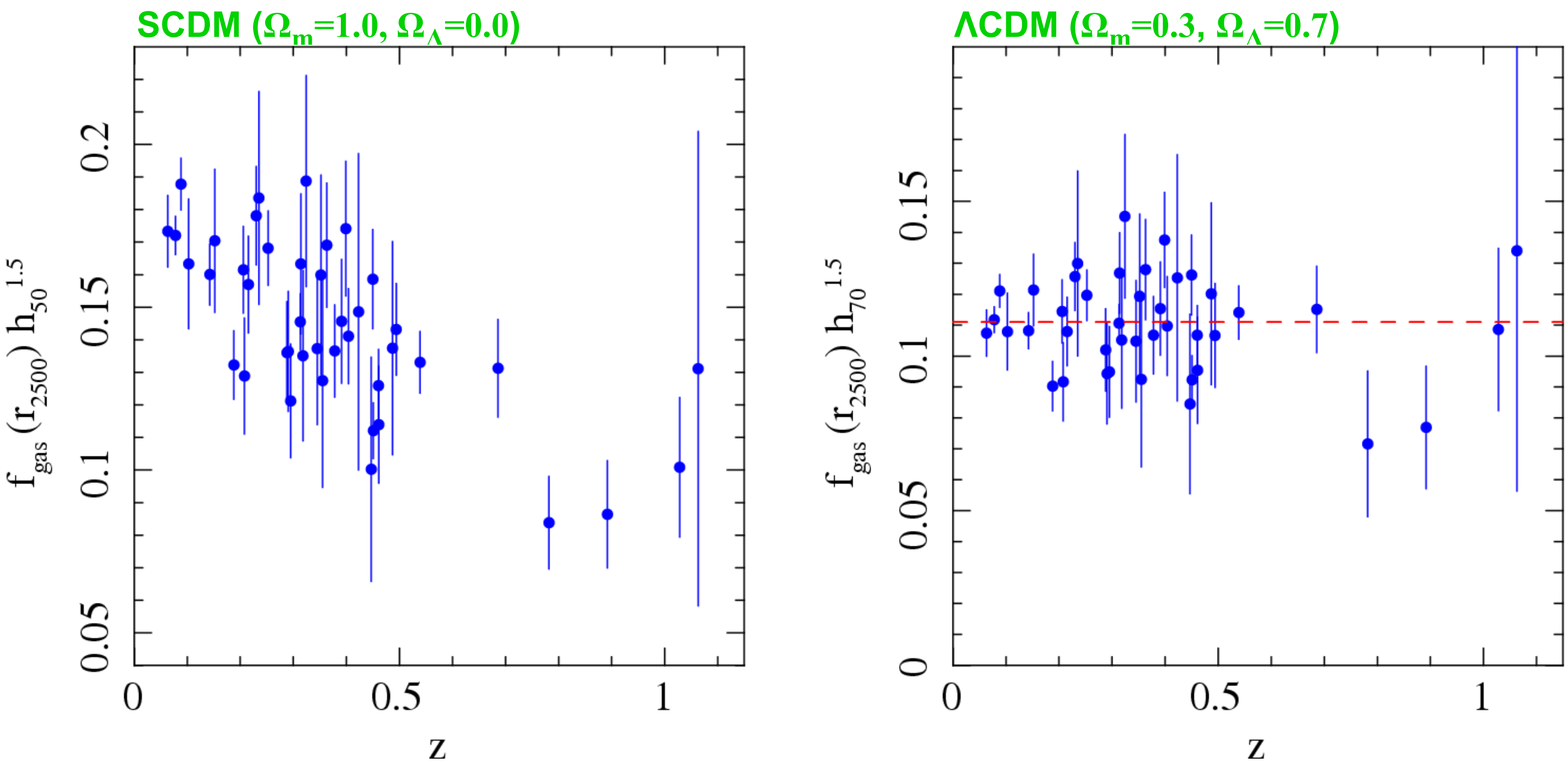
Simulations: (non-radiative)

For large (kT>5keV) relaxed clusters simulations suggest little evolution of depletion factor b(z) within z<1.

So we expect the observed $f_{gas}(z)$ values to be approx. constant with z.

Precise prediction of b(z) is a key task for new hydro. simulations.

Chandra results on $f_{gas}(z)$



Brute-force determination of $f_{gas}(z)$ for two reference cosmologies:

→ Inspection clearly favours ΛCDM over SCDM cosmology.

To quantify: fit data with model which accounts for apparent variation in $f_{gas}(z)$ as underlying cosmology is varied $\rightarrow$ find best fit cosmology.

$$f_{gas}(z) = \frac{KA\gamma b(z)}{1+s(z)}\left(\frac{\Omega_b}{\Omega_m}\right)\left[\frac{d_A^{LCDM}(z)}{d_A^{model}(z)}\right]^{1.5}$$

Allowances for systematic uncertainties

Our full analysis includes a comprehensive and conservative treatment of potential sources of systematic uncertainty in current analysis.

1) The depletion factor (simulation physics, gas clumping etc.)

$b(z)=b_0(1+\alpha_b z)$ 20% uniform prior on b_0 (simulation physics)
10% uniform prior on α_b (simulation physics)

2) Baryonic mass in stars: define $s= f_{star}/f_{gas} =0.16h_{70}^{0.5}$

$s(z)=s_0(1+\alpha_s z)$ 30% Gaussian uncertainty in s_0 (observational uncertainty)
20% uniform prior on α_s (observational uncertainty)

3) Non-thermal pressure support in gas: (primarily bulk motions)

$\gamma= M_{true}/M_{X\text{-}ray}$ 10% (standard) or 20% (weak) uniform prior $1<\gamma<1.2$

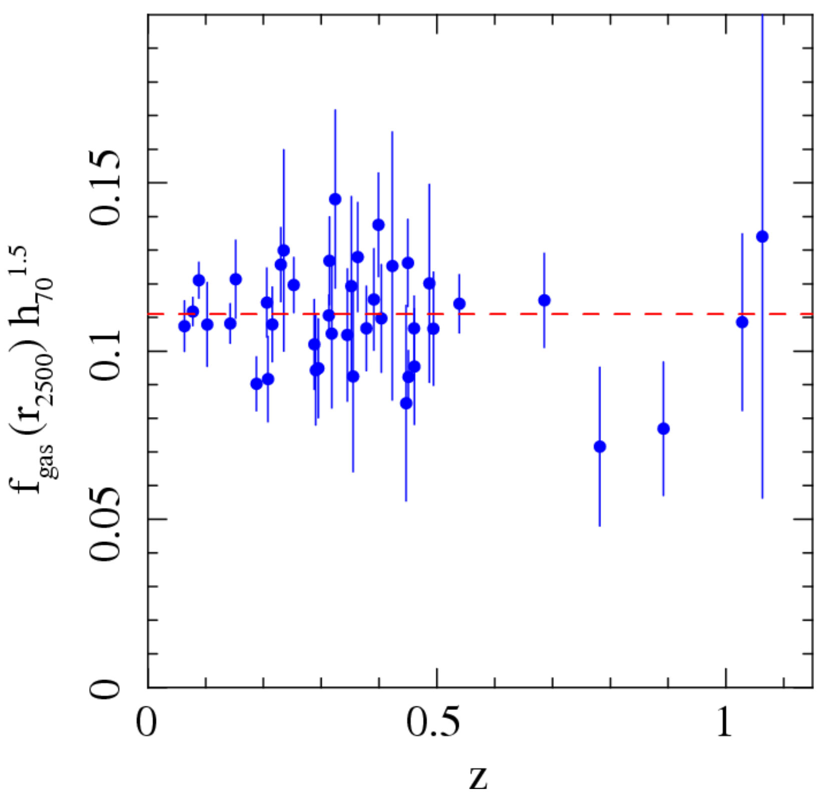
4) Instrument calibration, X-ray modelling

K 10% Gaussian uncertainty

With these (conservative) allowances for systematics

Model:

$$f_{gas}(z) = \frac{KA\gamma b(z)}{1+s(z)} \left(\frac{\Omega_b}{\Omega_m}\right) \left[\frac{d_A^{\,LCDM}(z)}{d_A^{\,model}(z)}\right]^{1.5}$$



Results (ΛCDM)

Full allowance for systematics + standard priors:
($\Omega_b h^2$=0.0214±0.0020, h=0.72±0.08)

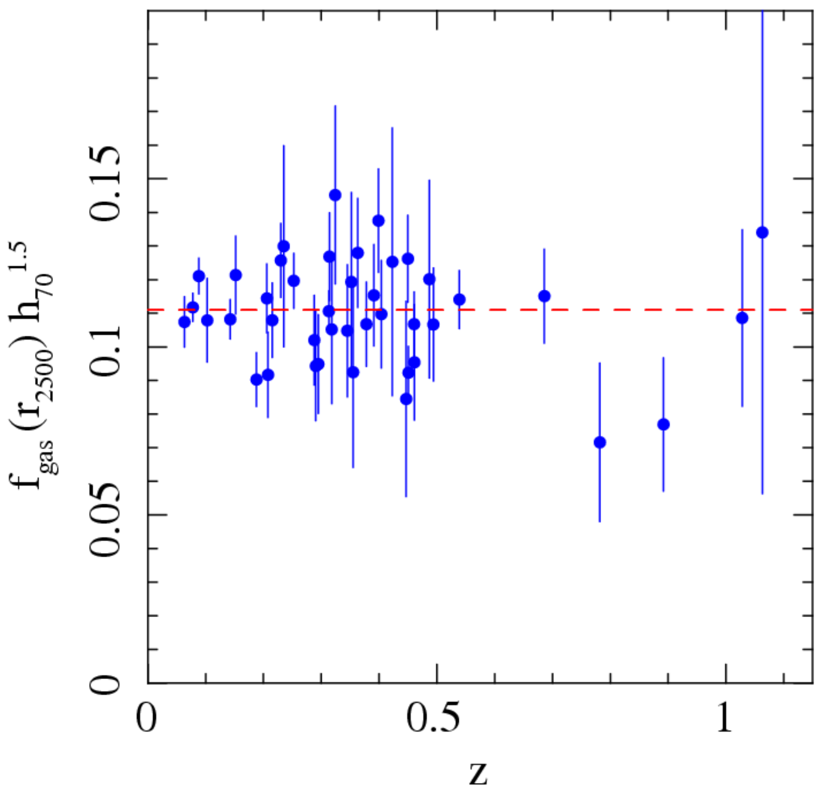
Best-fit parameters (ΛCDM):

Ω_m=0.27±0.06, Ω_Λ=0.86±0.19

(Note also good fit: χ^2=41.5/40)

Important

The low systematic scatter in the f_{gas}(z) data



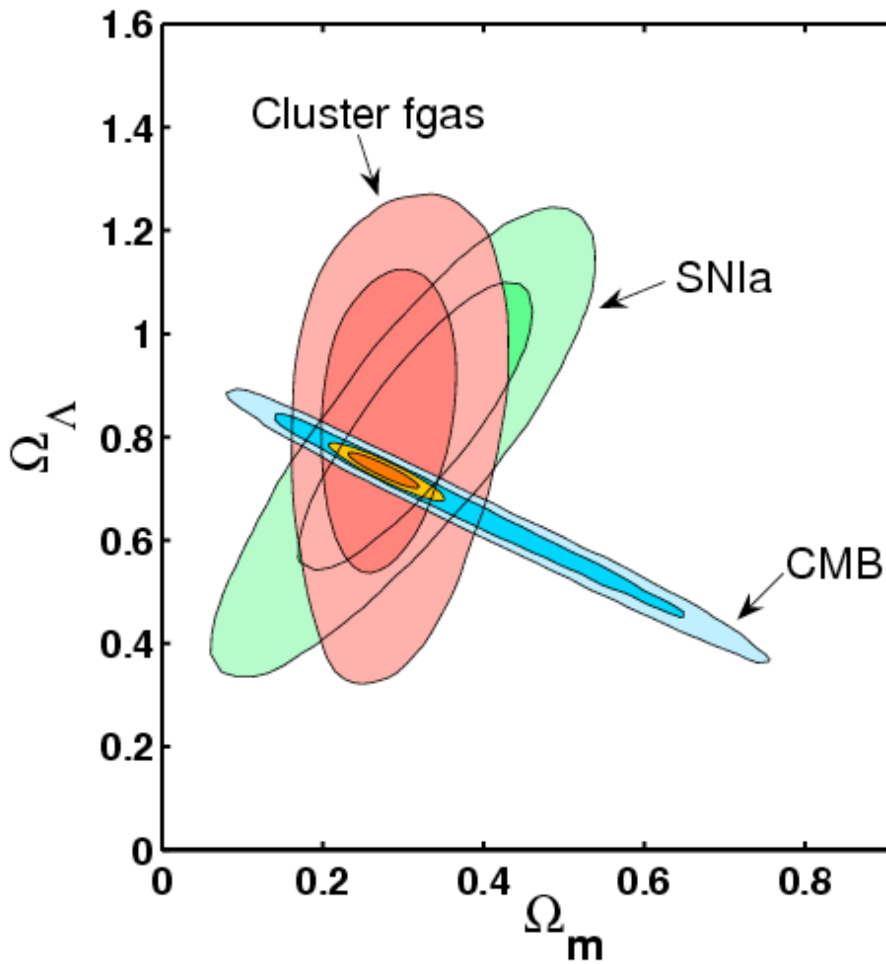
The χ^2 value is acceptable even though rms scatter about the best-fit model is only 15% in fgas, or 10% in distance.

Weighted-mean scatter only 7.2% in fgas or 4.8% in distance). c.f. SNIa, for which systematic scatter detected at ~7% level (distance).

Consistent with expectation from simulations (e.g. Nagai et al. '07)

The low systematic scatter in f_{gas}(z) data offers the prospect to probe cosmic acceleration to high precision using the next generation of X-ray observatories e.g. Constellation-X (Rapetti & Allen, astro-ph/0710.0440).

Comparison of independent constraints (ΛCDM)



Allen et al 2008

f_{gas} analysis: 42 clusters including standard $\Omega_b h^2$, and h priors and full systematic allowances

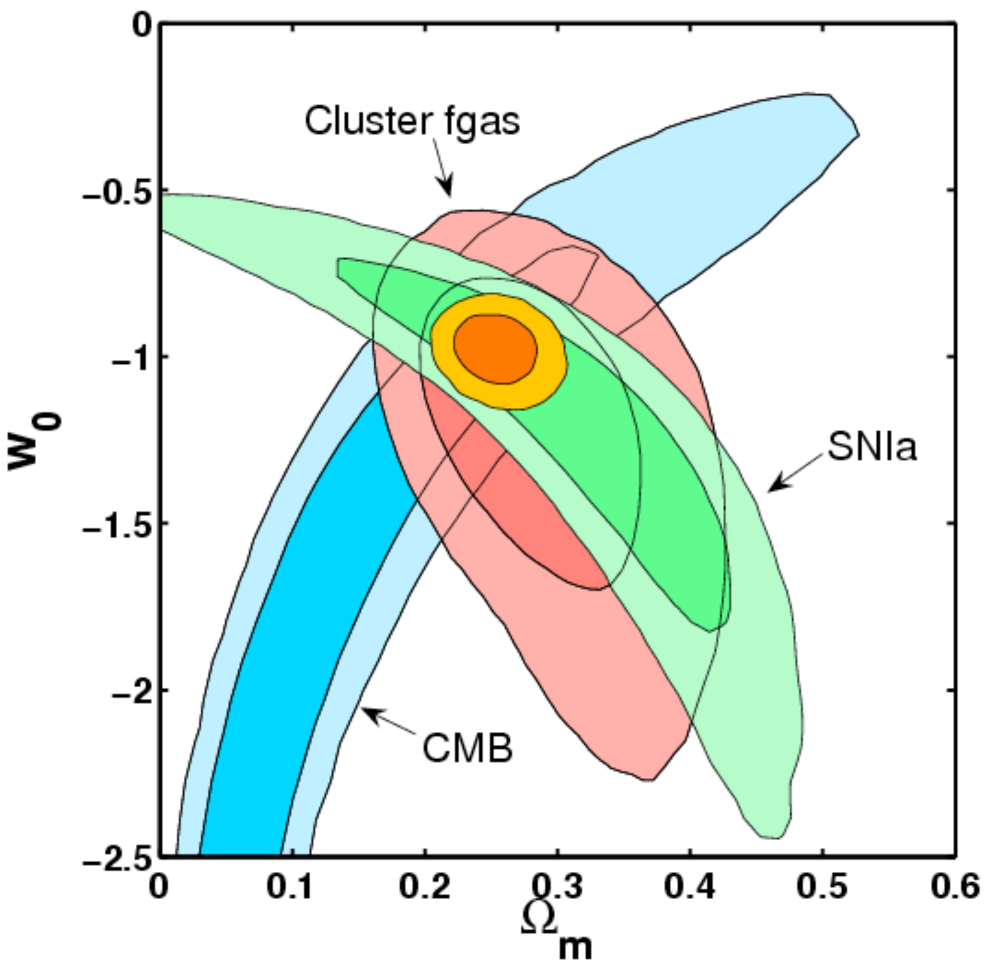
CMB data (WMAP-3yr +CBI+ACBAR + prior $0.2<h<2.0$)

Supernovae data from Davis et al. '07 (192 SNIa, ESSENCE+ SNLS+HST+nearby).

Combined constraint (68%)

$\Omega_m = 0.275 \pm 0.033$
$\Omega_\Lambda = 0.735 \pm 0.023$

Dark energy equation of state:



<u>Constant w model:</u>

Analysis assumes flat prior.

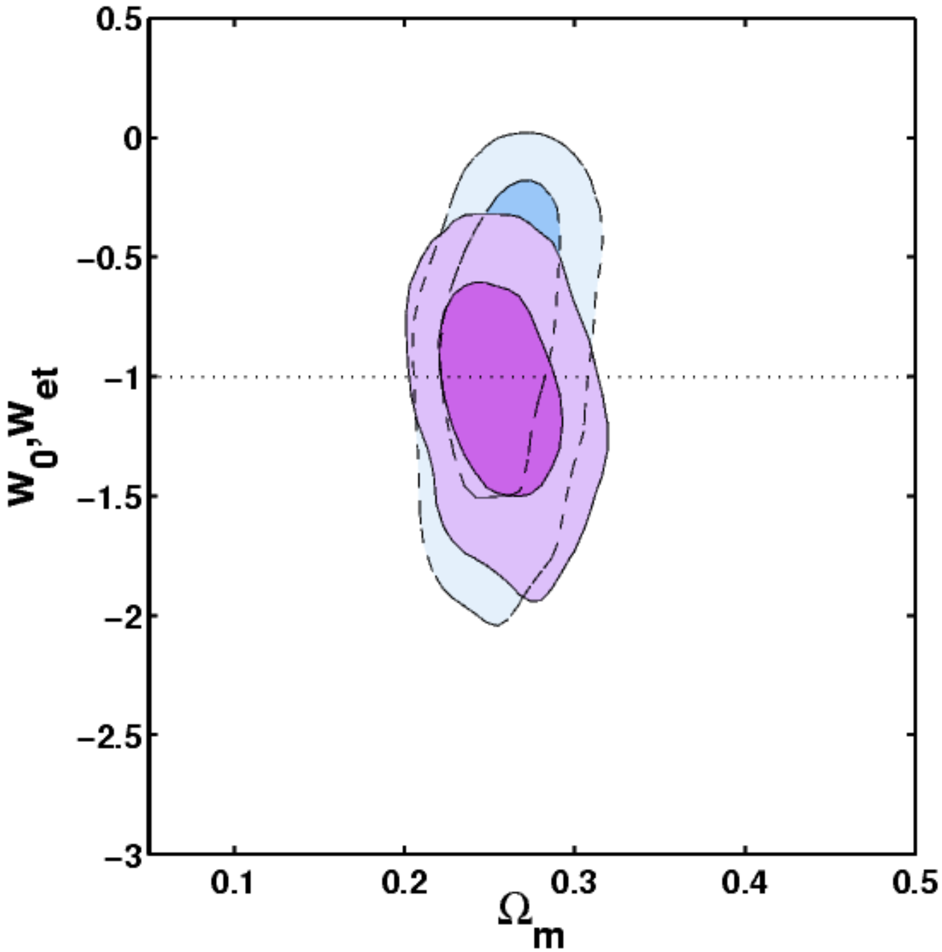
68.3, 95.4% confidence limits for all three data sets consistent with each other.

<u>Combined constraints (68%)</u>

$\Omega_m = 0.253 \pm 0.021$
$w_0 = -0.98 \pm 0.07$

Note: combination with CMB data removes the need for $\Omega_b h^2$ and h priors.

Results for evolving equation of state (flat prior)



Free transition redshift:

$$w = \frac{w_0 z_t + w_{et} z}{z + z_t}$$

Allow $0.5<1/(1+z_t)<0.95$.

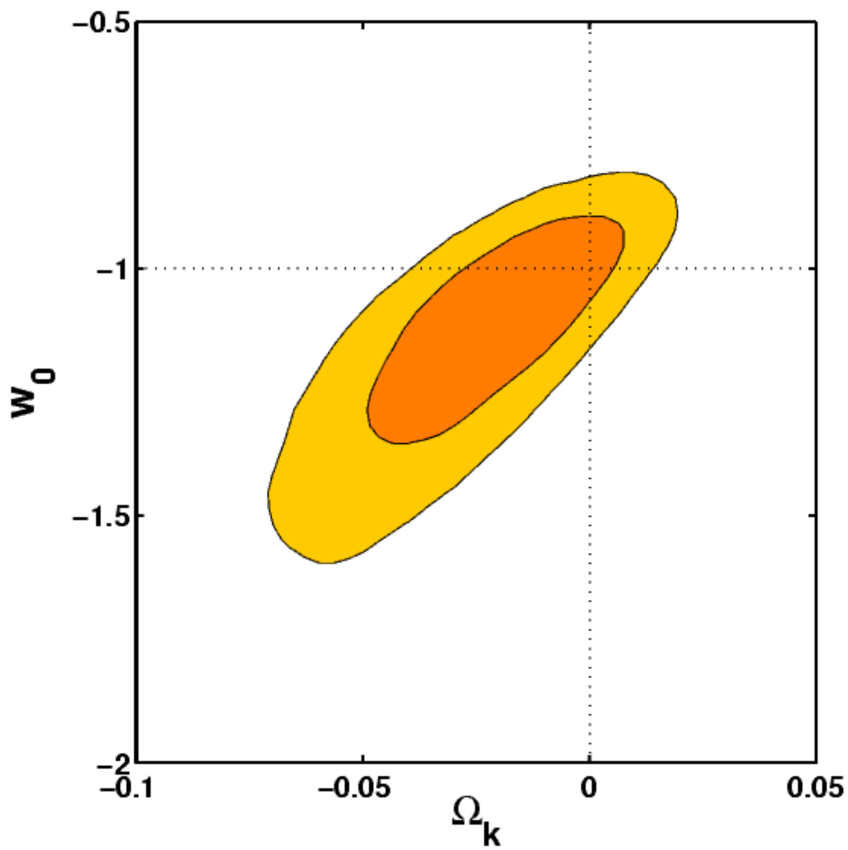
Marginalized constraints (68%)

w_0 = -1.05 (+0.31,-0.26)
w_{et} =-0.83 (+0.48,-0.43)

Conclude: fgas+CMB+SNIa data consistent with cosmological constant model.

Relaxing the flat prior (constant w model)

Due to the complementary nature of the fgas+CMB+SNIa data, one can drop the assumption of Ω_K=0 in the analysis and still obtain tight constraints on DE.



Marginalized constraints (68%)

Ω_M = 0.278 (+0.064, -0.050)

Ω_{DE} = 0.732 (+0.040, -0.046)

w_0 = -1.08 (+0.13, -0.19)

Ω_K = -0.011 (+0.015, -0.017)

Probing cosmology with X-ray clusters

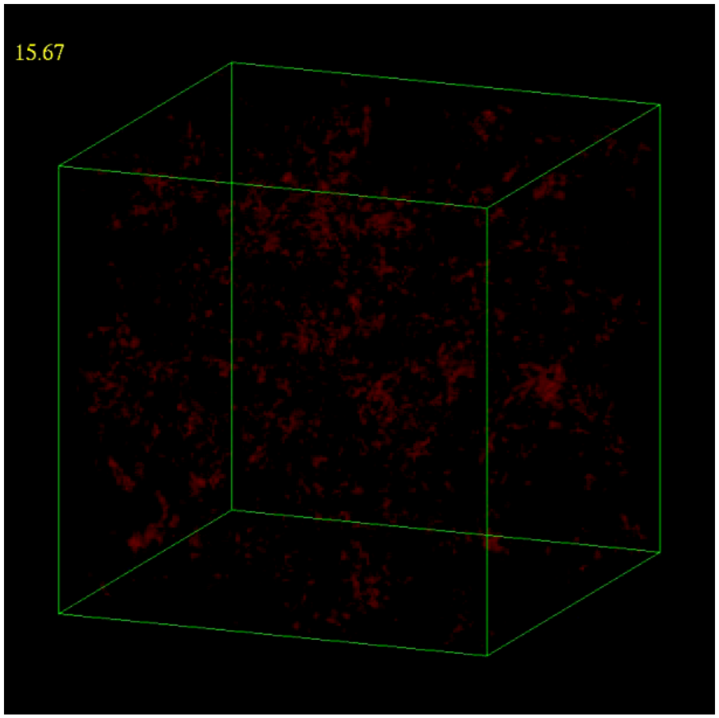
2. The growth of cosmic structure (evolution of the XLF)

Mantz et al. 2008, MNRAS, in press (astro-ph/0709.4294)

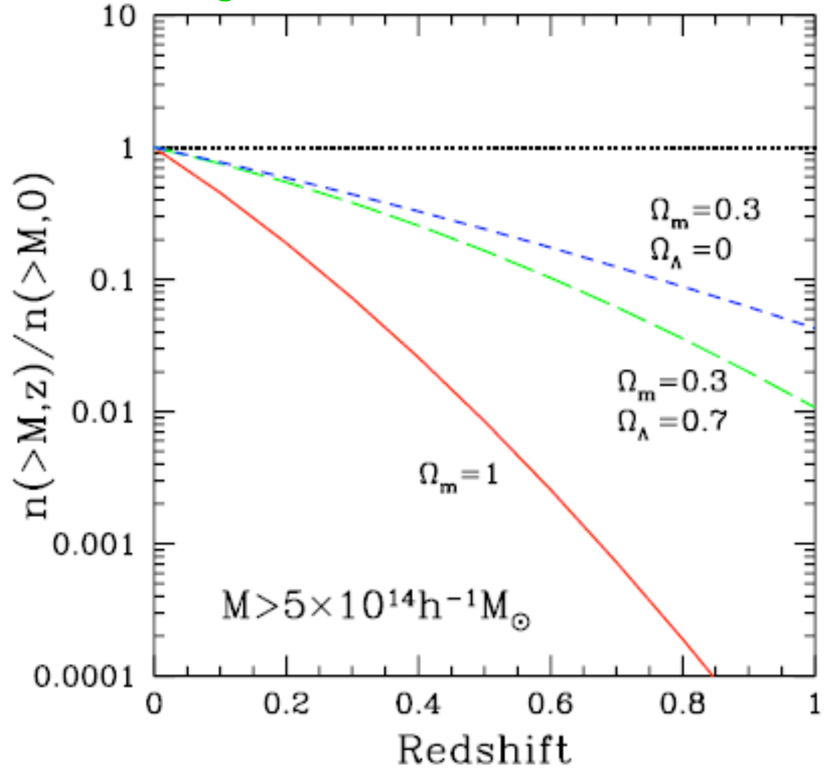
(See also e.g. Borgani et al ’01; Reiprich & Bohringer ’02; Seljak ’02; Viana et al ’02; Allen et al. ’03; Pierpaoli et al. ’03; Vikhlinin et al. ’03; Schuecker et al ’03; Voevodkin & Vikhlinin ’04; Henry ’04; Dahle ’06 etc.)

Cluster growth of structure experiments

Moore et al.



Borgani '06



The observed growth rate of galaxy clusters provides (highly) complementary constraints on dark matter and dark energy to those from distance measurements.

Ingredients for cluster growth of structure experiments

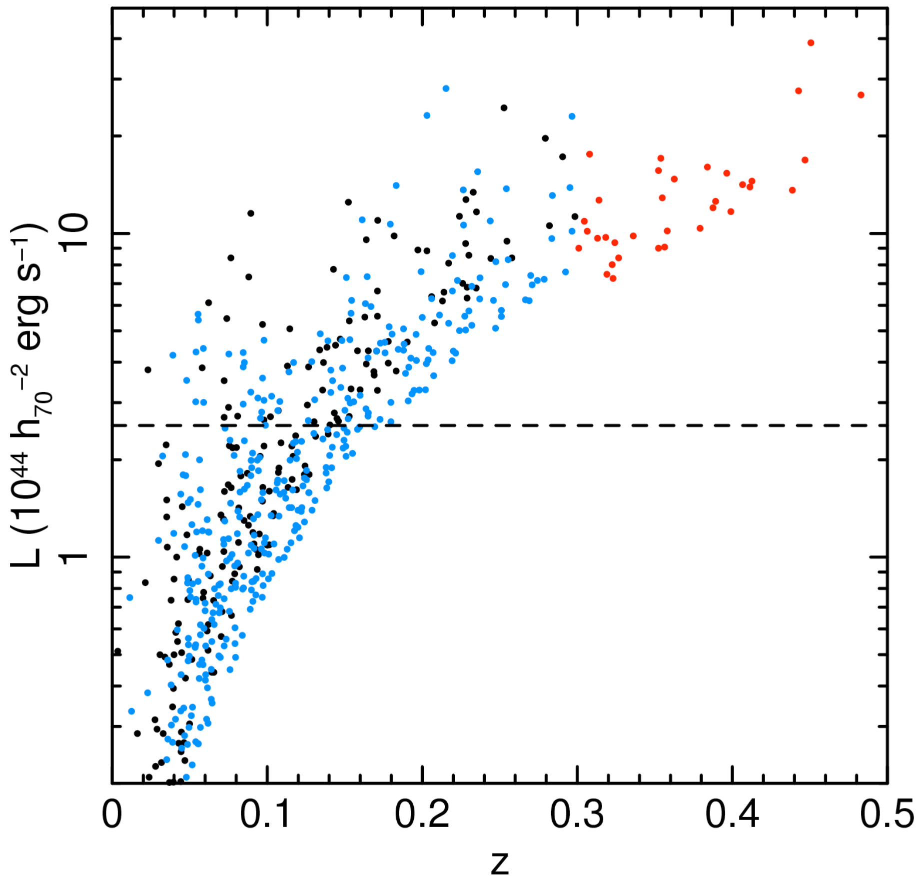
[THEORY] The predicted mass function for clusters, n(M,z), as a function of cosmological parameters (σ_8,Ω_m,w_0, w_a etc) $\leftarrow$ in hand from current + near future numerical simulations (e.g. Jenkins et al. ’01)

[CLUSTER SURVEY] A large, wide-area, clean, complete cluster survey, with a well defined selection function.

Current leading work based on ROSAT X-ray surveys. Future important work based on new SZ (SPT, Planck) and optical catalogues as well as next-generation X-ray surveys (eROSITA/WFXT).

[SCALING RELATION] A tight, well-determined scaling relation between survey observable (e.g. Lx) and mass, with minimal intrinsic scatter.

The BCS, REFLEX and MACS X-ray survey data



BCS (Ebeling et al. ’98, ’00)
Fx>4.4×10^{-12} $ergcm^{-2}s^{-1}$.
78 clusters above Lx limit.

REFLEX (Bohringer et al ’04).
Fx>3.0×10^{-12} $ergcm^{-2}s^{-1}$.
130 clusters above Lx limit.

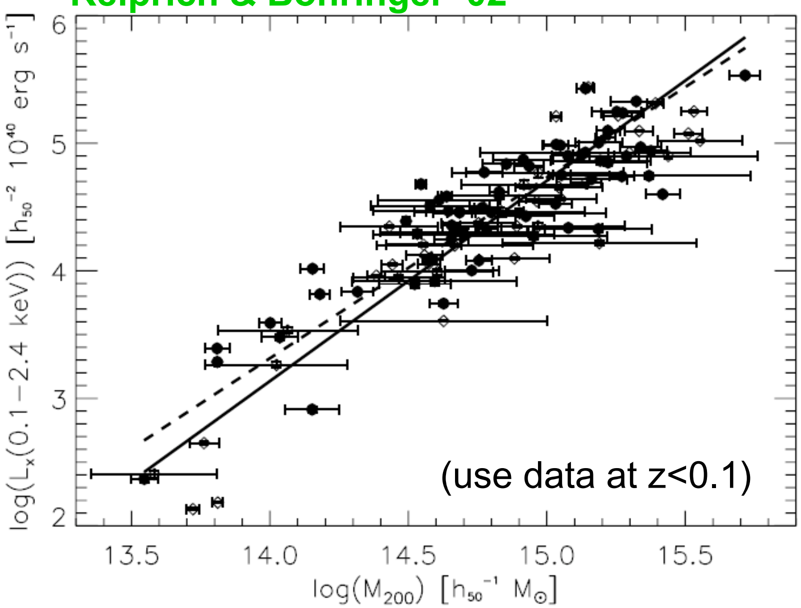
MACS (Ebeling et al. ’01, ’07)
Fx>2.0×10-12 ergcm-2s-1 .
36 clusters above Lx limit.

244 clusters with Lx > 2.55×10^{44} h_{70}^{-2} erg s^{-1}

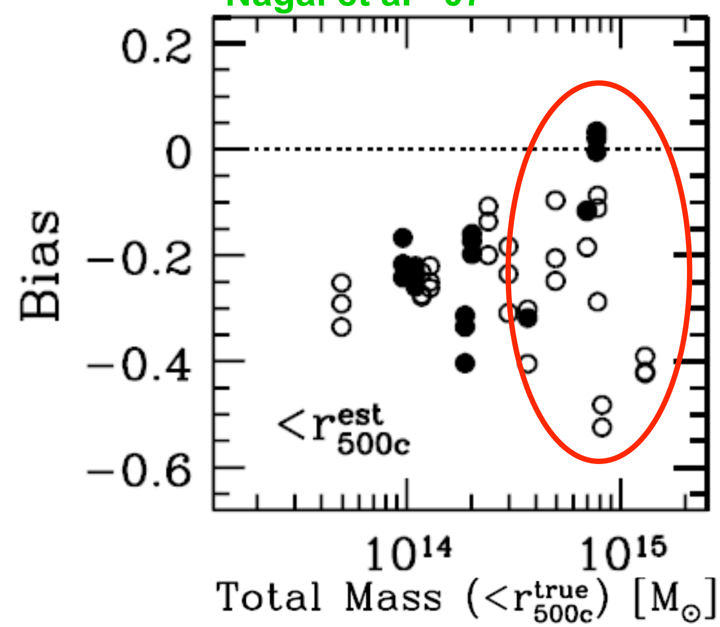
To minimize systematic uncertainties, our analysis is limited to most massive, most X-ray luminous clusters with Lx > 2.55×10^{44} h_{70}^{-2} erg s^{-1} (dashed line)

Scaling relation: X-ray luminosity and mass

Reiprich & Bohringer '02



Nagai et al '07



M,L both from X-ray observations. Major uncertainty is scale of bulk/turbulent motions in X-ray emitting gas. Can correct for this using hydro. simulations.

Based on sims assume bias -25(±5)% and scatter ±15(±3)% due to bulk motions.

Alternatively, can measure masses via gravitational lensing. Independent method with very different uncertainties. Work on this is underway….

Fitting the mass-luminosity data

$$E(z)M_{500} = M_0(1+z)^{\gamma}\left(\frac{L}{E(z)}\right)^{\beta}$$

Take log → $Y = \alpha + \beta X_1 + \gamma X_2$ with

$$Y = \log_{10}\left(\frac{E(z)M_{500}}{M_{\odot}}\right) \qquad \alpha = \log_{10}\left(\frac{M_0}{M_{\odot}}\right) \qquad X_1 = \log_{10}\left(\frac{L}{E(z)10^{44}\, erg\ s^{-1}}\right) \qquad X_2 = \log_{10}(1+z)$$

Note: includes allowance for non-similar evolution. We extrapolate measured masses to M_{vir} using NFW model with appropriate range of `concentration'.

Use modified chi-square to associate goodness-of-fit with M-L parameters in presence of intrinsic scatter. δ fixed to give best-fit reduced chi-square ~1.

$$\tilde{\chi}^2 = \sum_j \frac{(\alpha + \beta X_{1,j} - Y_j)^2}{\varepsilon_{Y,j}^2 + \delta}$$

Estimated log-normal intrinsic dispersion in luminosity for a given mass.

$$\hat{\eta}_0^2 = \frac{1}{\nu}\sum_j\left[\left(\frac{Y_j - \alpha_f}{\beta_f} - X_{1,j}\right)^2 - \varepsilon_{X_1,j}^2 - \left(\frac{\varepsilon_{Y,j}}{\beta_f}\right)^2\right]$$

Cosmological analysis

Fitted model parameters: **h, $\Omega_b h^2$, $\Omega_c h^2$, σ_8, n_s, w, A, α, β, γ, η_0, η_1, B.**

Log likelihood $\boxed{l = l_{\alpha\beta} + l_\eta + l_{XLF}}$ with

$l_{\alpha\beta} = -\tilde{\chi}^2 / 2$ (M-L goodness of fit), $l_\eta = (k-1)\ln(x) - \frac{x}{\theta} - k\ln(\theta)$

(2nd term penalizes models for which measured intrinsic dispersion in mass-luminosity relation, $\hat{\eta}_0$, is different from model dispersion, η_0) and

$$l_{XLF} = \sum_i \ln\left(d_L^2 \frac{dV}{dz} \frac{d\tilde{n}}{d\hat{L}}\bigg|_{z_i, \hat{L}_i} \right) + \int dz d\hat{L} \frac{dV}{dz} \frac{d\tilde{n}}{d\hat{L}}$$

true luminosity, L
detected luminosity, $\hat{L}$
predicted no. density, $\tilde{n}$

with

$$\frac{d\tilde{n}(z, \hat{L})}{d\hat{L}} = f_{sky}(z, \hat{L}) \int_0^\infty dL P(\hat{L} \mid L) \int_0^\infty dM_{500} P(L \mid M_{500}) \frac{dn(z, M_{vir})}{dM_{vir}} \frac{M_{vir}}{M_{500}}$$

Priors and allowances for systematic uncertainties

Our full analysis includes the following priors and conservative allowances for systematic uncertainties:

1) Cosmological parameters (not needed if CMB data employed)

Hubble constant, h	0.72±0.08 (standard), 0.72±0.24 (weak)
baryon density, $\Omega_b h^2$	0.0214±0.0020 (standard), 0.0214±0.0060 (weak)
spectral index, n_s	0.95 fixed (standard), $0.9<n_s<1.0$ (weak)

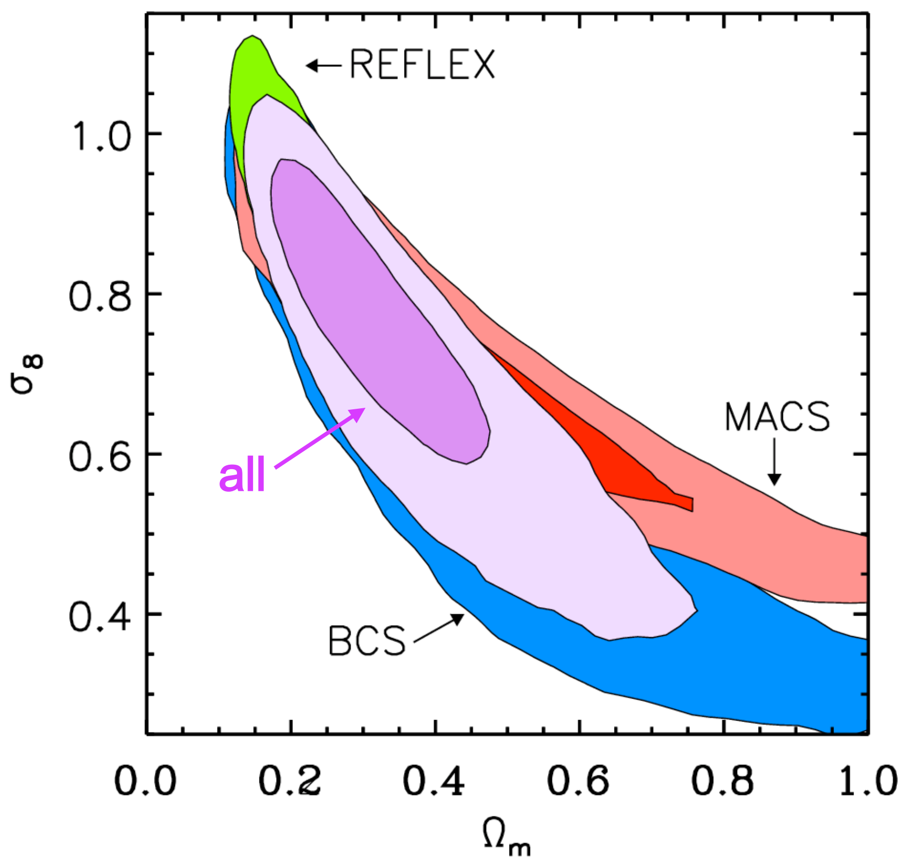
2) Jenkins mass function

normalization, A	±20% (standard), ±40% (weak)

3) Mass-luminosity relation

non-thermal pressure support	25±5% (standard), 25±10% (weak)
non-thermal pressure scatter	15±3% (standard), 15±6% (weak),
evolution of M-L scatter	±20% uniform (standard), ±40% (weak)
non-self similar M-L evolution	±20% uniform (standard), ±40% (weak)

Results on σ_8, Ω_m (flat ΛCDM model)



BCS: Ω_m = 0.26 (+0.25, -0.09)
σ_8 = 0.78 (+0.10, -0.37)

REFLEX: Ω_m = 0.20 (+0.10,-0.04)
σ_8 = 0.85 (+0.10, -0.09)

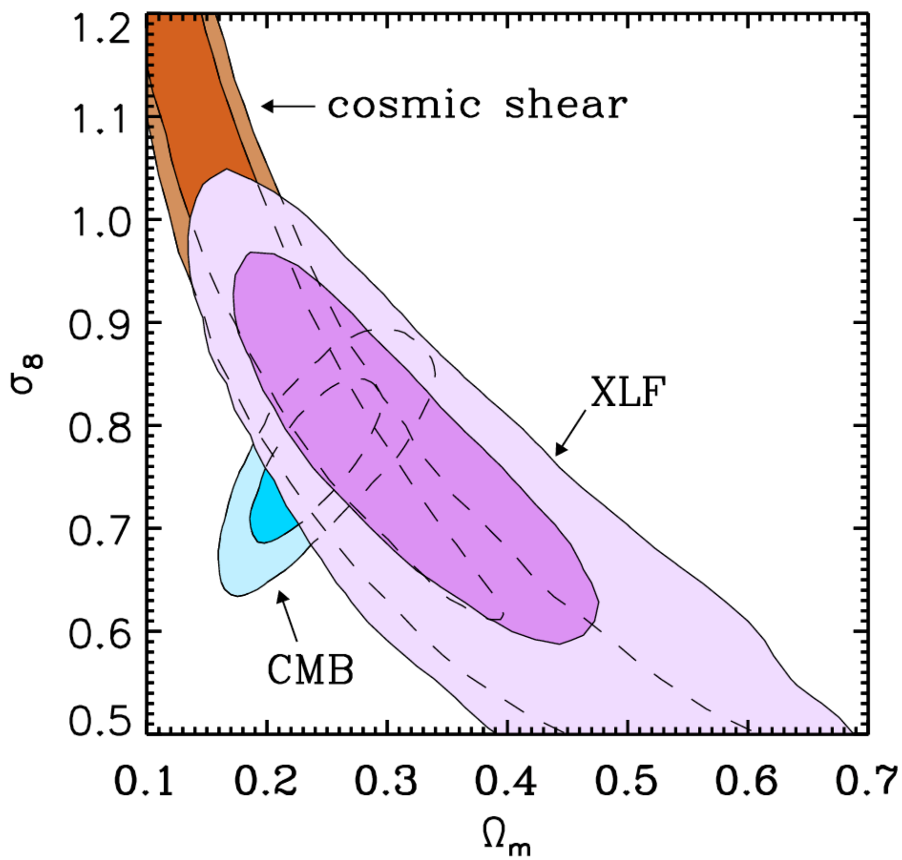
MACS: Ω_m = 0.30 (+0.24, -0.10)
σ_8 = 0.73 (+0.14, -0.13)

Combined constraints (68%)

Ω_m = 0.28 (+0.11, -0.07)
σ_8 = 0.78 (+0.11,-0.13)

Mantz et al 2008

Comparison with best other current results on σ_8, Ω_m



<u>Flat ΛCDM model:</u>

X-ray cluster number counts
(Mantz et al. '08; this study)

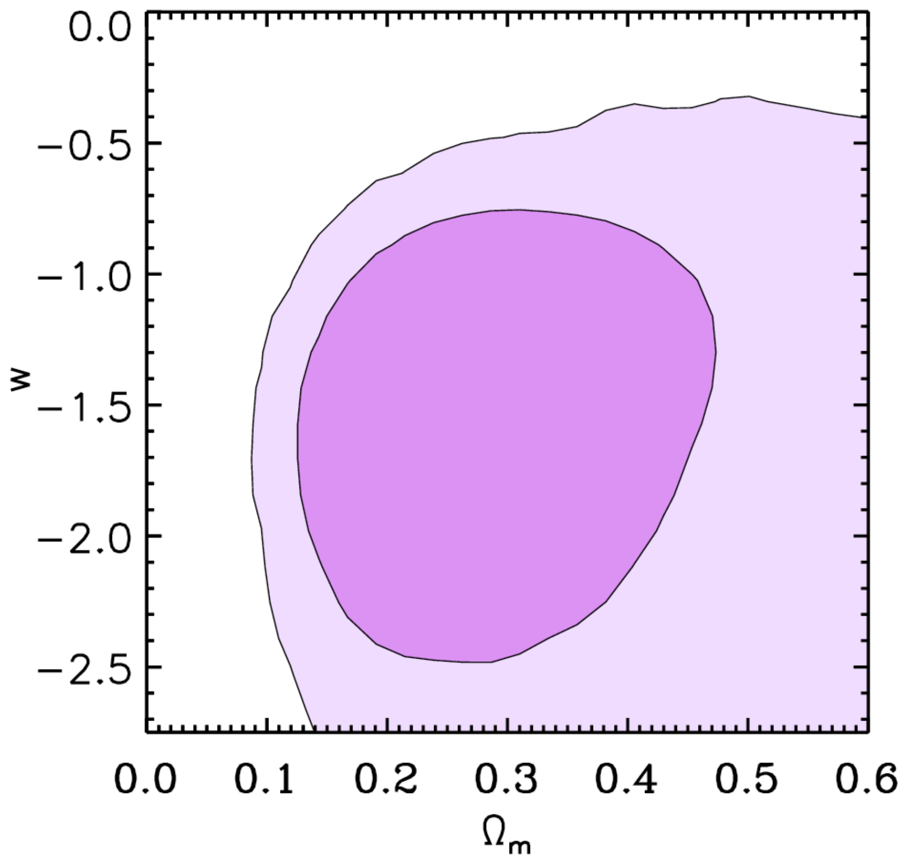
CMB data (WMAP3)

Cosmic Shear (weak lensing)
100 square degree survey
(Benjamin et al. '07)

68.3, 95.4% confidence
limits shown in all cases.

Good agreement between results from 3 independent astrophysical methods

Results on dark energy



<u>Flat, constant w model:</u>

REFLEX+BCS+MACS (z<0.7).
242 clusters, Lx>2.55e44 erg/s.
2/3 sky. n(M,z) only.

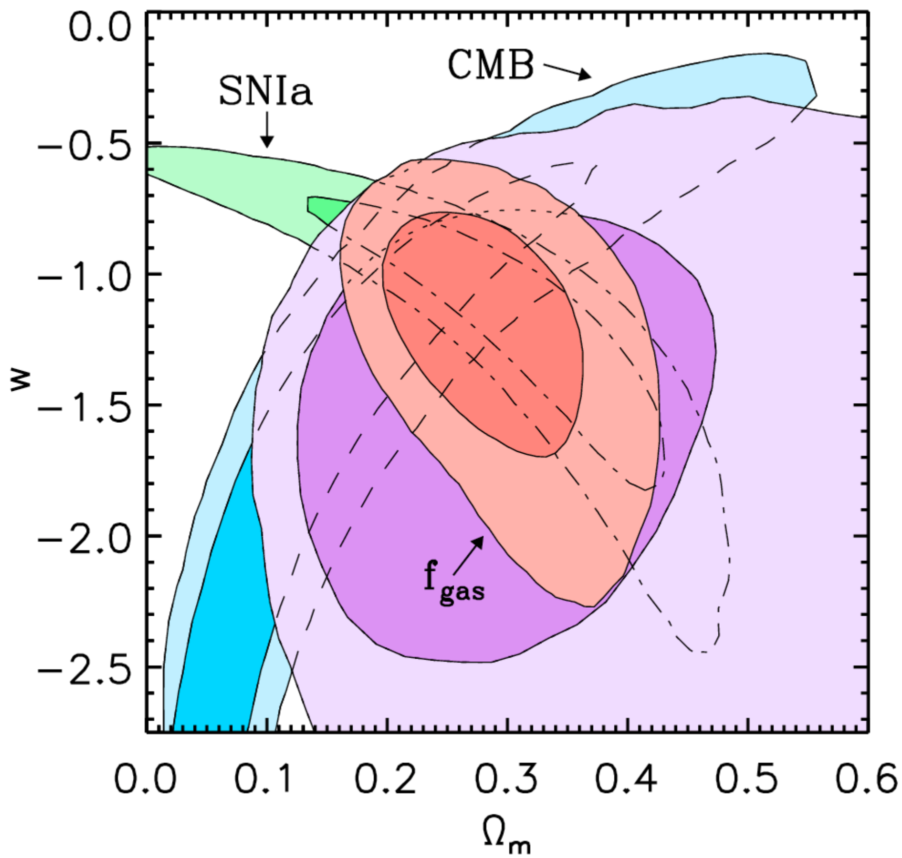
68.3, 95.4% confidence limits

<u>Marginalized constraints (68%)</u>

Ω_m = 0.24 (+0.15, -0.07)
σ_8 = 0.85 (+0.13, -0.20)
w = -1.4 (+0.4,-0.7)

First constraint on w from a cluster growth of structure experiment

Comparison with best other constraints on dark energy



Flat, constant w model:

X-ray cluster number counts (Mantz et al. '08)

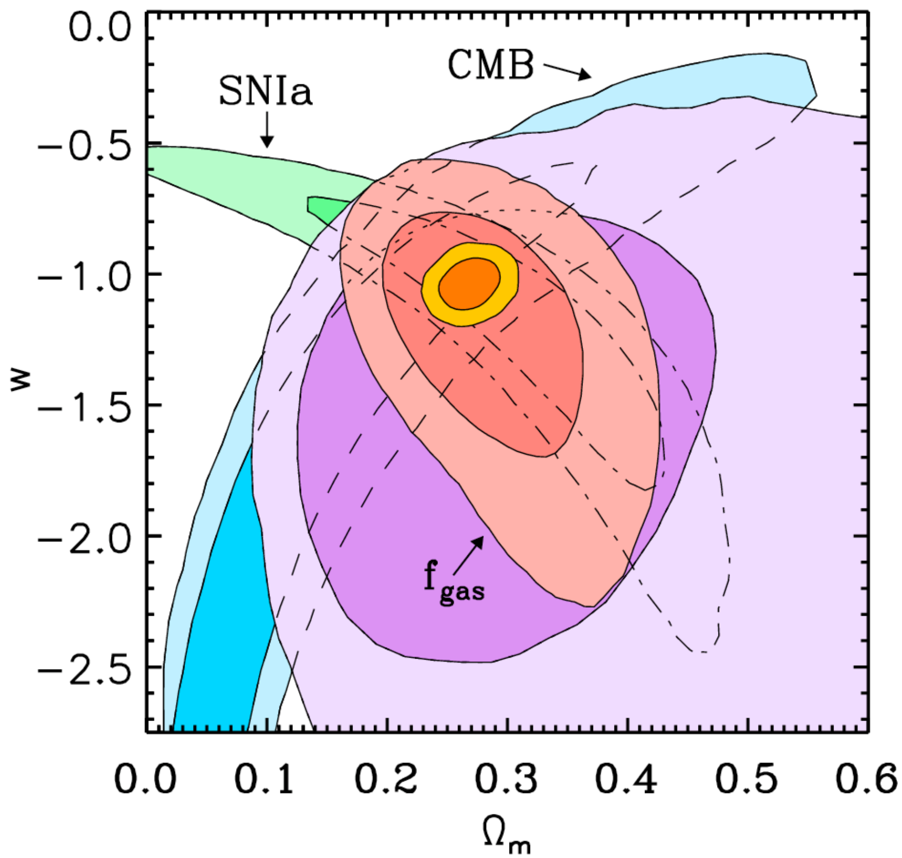
X-ray cluster f_{gas} analysis (Allen et al '08)

CMB data (WMAP-3yr) (Spergel et al '07)

SNIa data (Davis et al. '07 (192 SNIa, ESSENCE+ SNLS+HST+nearby).

Good agreement between all 4 completely independent techniques. All data sets independently consistent with cosmological constant (w = -1) model.

Combined constraint on dark energy



Flat, constant w model:

XLF+fgas+WMAP3+SNIa

Marginalized constraints (68%)

Ω_m = 0.269±0.016
σ_8 = 0.82±0.03
w = -1.02±0.06

Combined constraint consistent with cosmological constant to 6% precision.

Conclusions

$f_{gas}(z)$ data for largest relaxed clusters → tight constraints on $\Omega_{M,}$ Ω_Λ and w via absolute distance measurements.

Ω_M=0.27±0.06 Ω_Λ=0.86±0.19 (w= -1.14±0.31)

Measurements of the growth of X-ray luminous clusters spanning 0<z<0.7 → independent constraints on $\Omega_{M,}$ σ_8 and w.

Ω_M=0.28(+0.11,-0.07) σ_8=0.78(+0.11,-0.13) (w= -1.4 +0.4,-0.7)

The combination of X-ray growth of structure, fgas, CMB and SNIa data already constrain dark energy to be consistent with cosmological constant at 6% level.

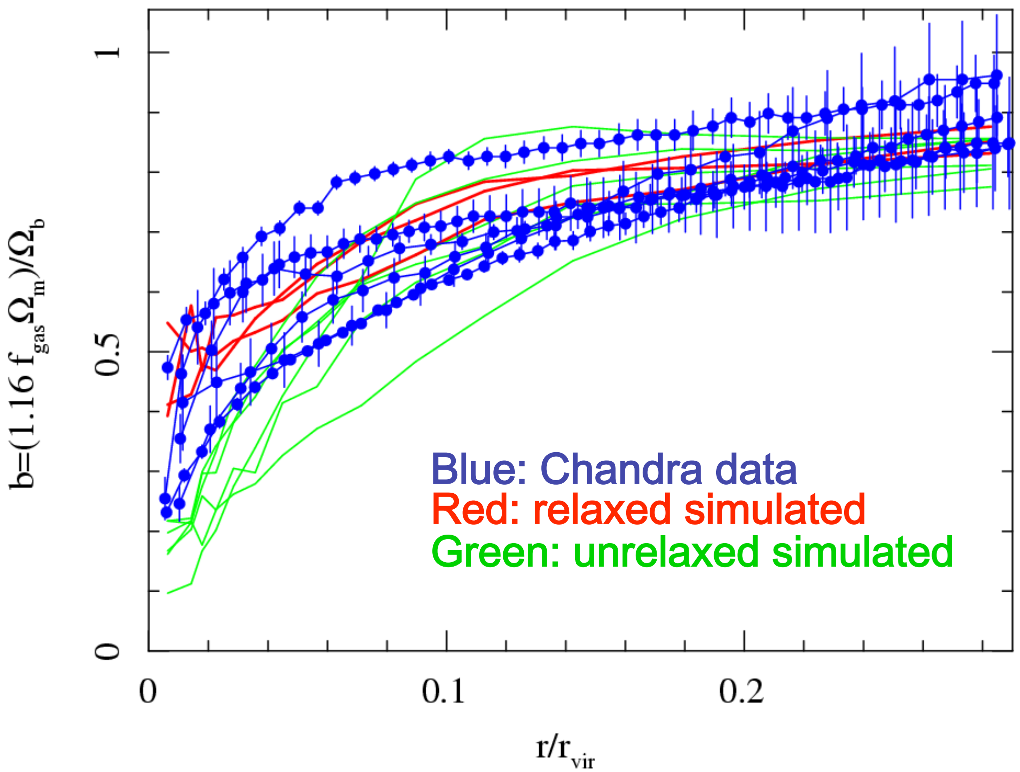
Ω_M=0.269±0.016 σ_8=0.82±0.03 w= -1.02±0.06

Immediate next steps (current data): explore implications for dark energy vs. modified gravity models, species-summed neutrino mass etc.

Future: more X-ray data, gravitational lensing studies (M-L), improved hydro. simulations, new X-ray/SZ surveys, Constellation-X/XEUS.

Further checks for systematics in the fgas experiment

Comparison of observed and simulated fgas profiles



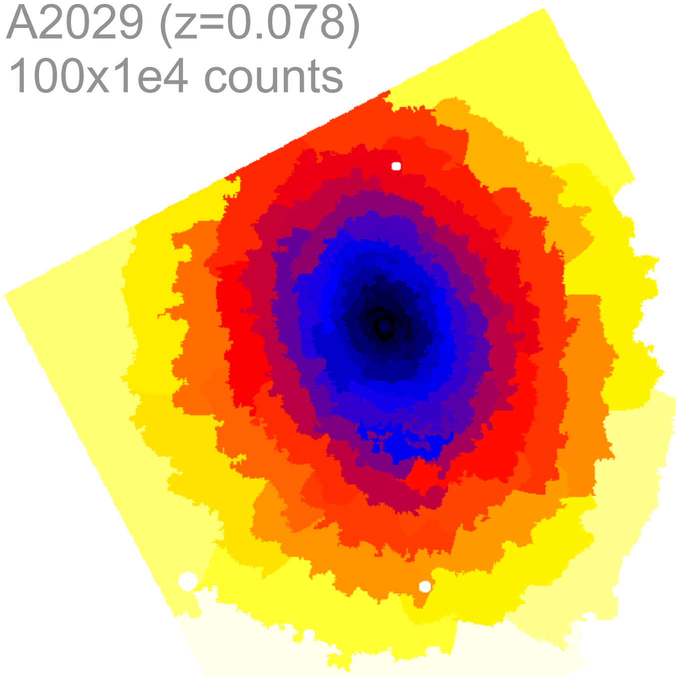
Good agreement with non-radiative sims.

New large hydro. simulations, constrained to match X-ray+optical observations, should significantly reduce uncertainties b(z) → improved constraints.

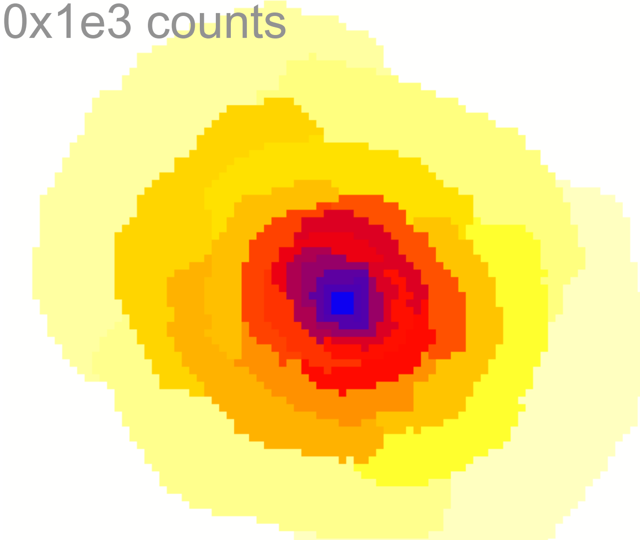
Checks on hydrostatic assumption 1

X-ray pressure maps: (from projected kT and emission measure)

A2029 (z=0.078)
100x1e4 counts



MS2137-2353 (z=0.313)
40x1e3 counts



(Million et al., in preparation)

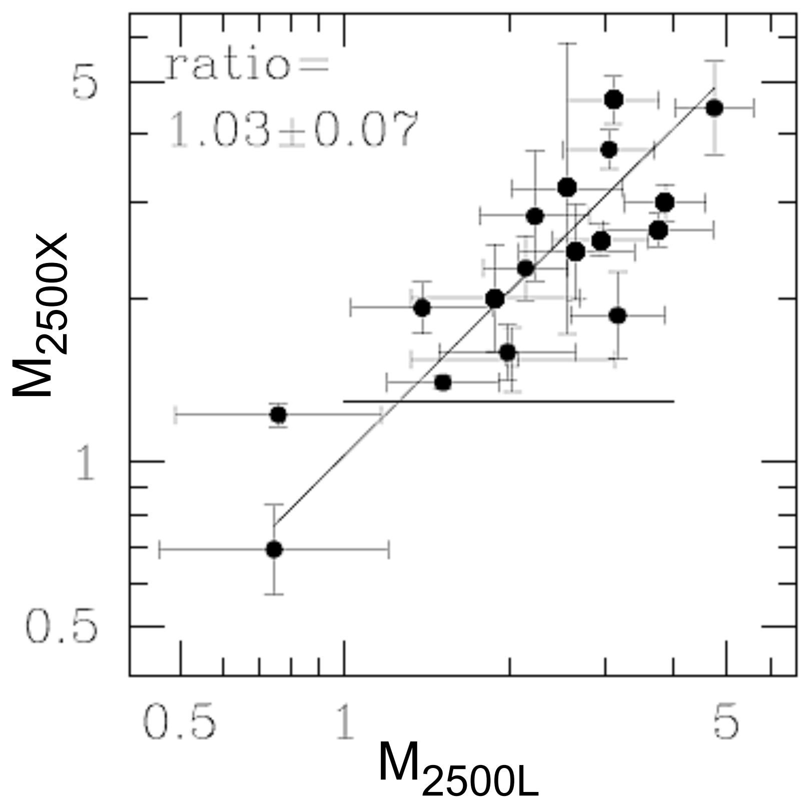
X-ray pressure maps can reveal departures from hydrostatic equilibrium.

Analysis confirms dynamically relaxed nature of target clusters.

Checks on hydrostatic assumption 2

Gravitational lensing: provides an independent way to measure cluster masses that is independent of the dynamical state of the matter .

Ambitious lensing study underway (with A. von der Linden, D. Applegate, P. Kelly, M. Bradac, M. Allen, G. Morris, D. Burke, P. Burchat, H. Ebeling): 50+ clusters with deep, multi-color Subaru+HST+spectroscopic data (in progress).

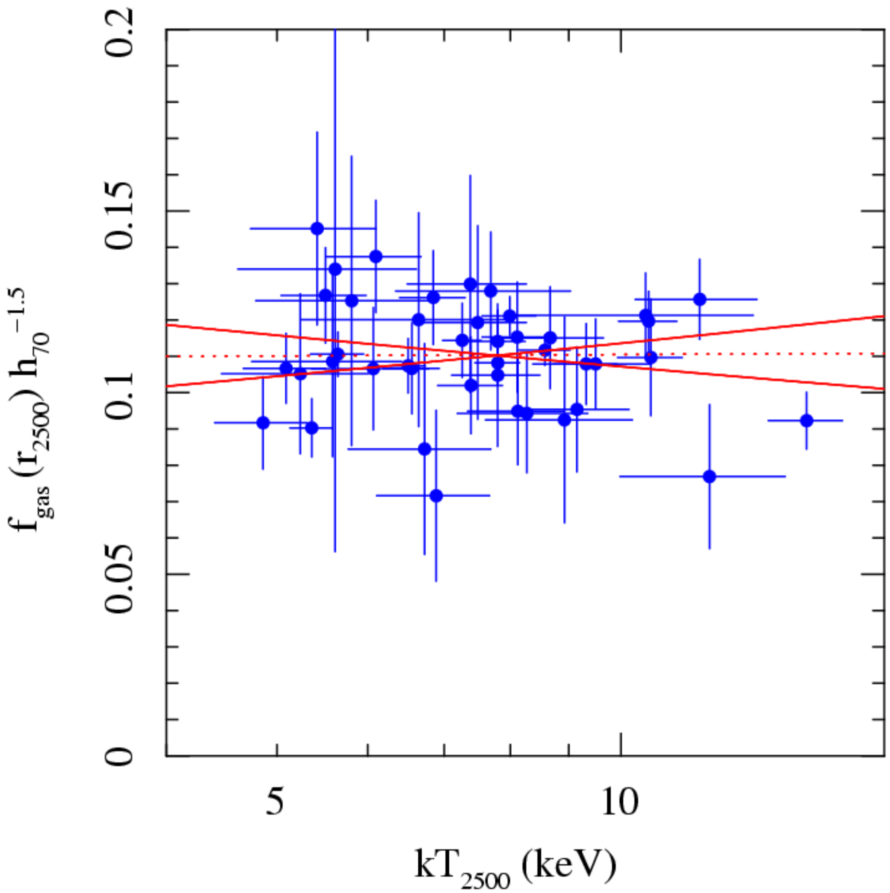


Also work by other groups.

Initial findings by Mahdavi et al. (2008) suggests little systematic offset between X-ray and lensing masses measured within r_{2500} on average.

See also Bradac et al 2008, ApJ, in press (astro-ph/0711.4850)

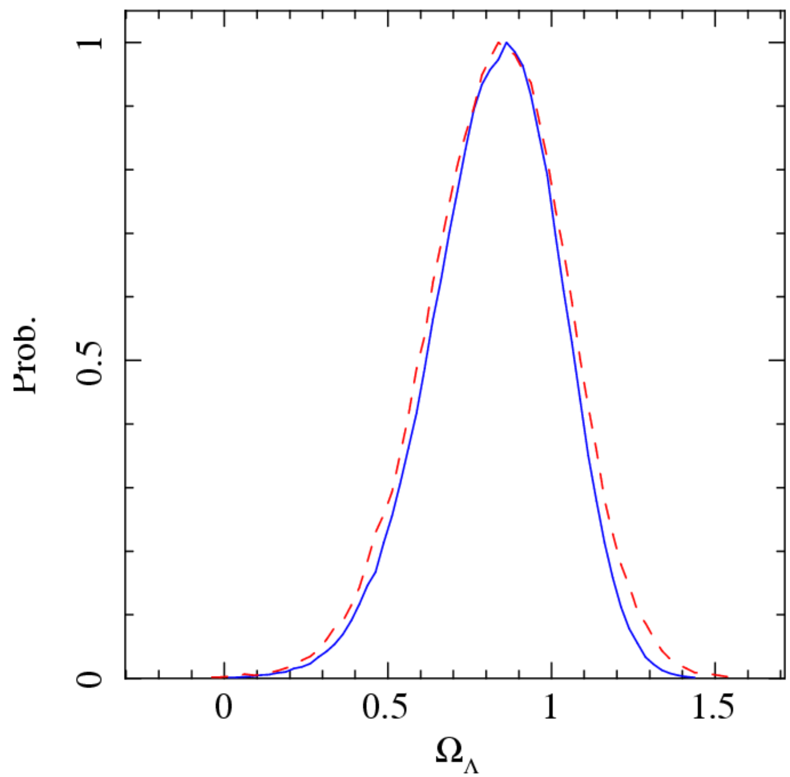
A systematic trend of f_{gas} with temperature?



We find no evidence for a trend of fgas with kT in the Chandra data for kT>5keV.

Best-fit power-law model is consistent with a constant. (plot shows 2-sigma limits).

Marginalized results on dark energy (ΛCDM)



Blue: standard priors on $\Omega_b h^2$,h.

$\Omega_\Lambda = 0.86 \pm 0.19$

Red: weak (3x) priors on $\Omega_b h^2$, h.

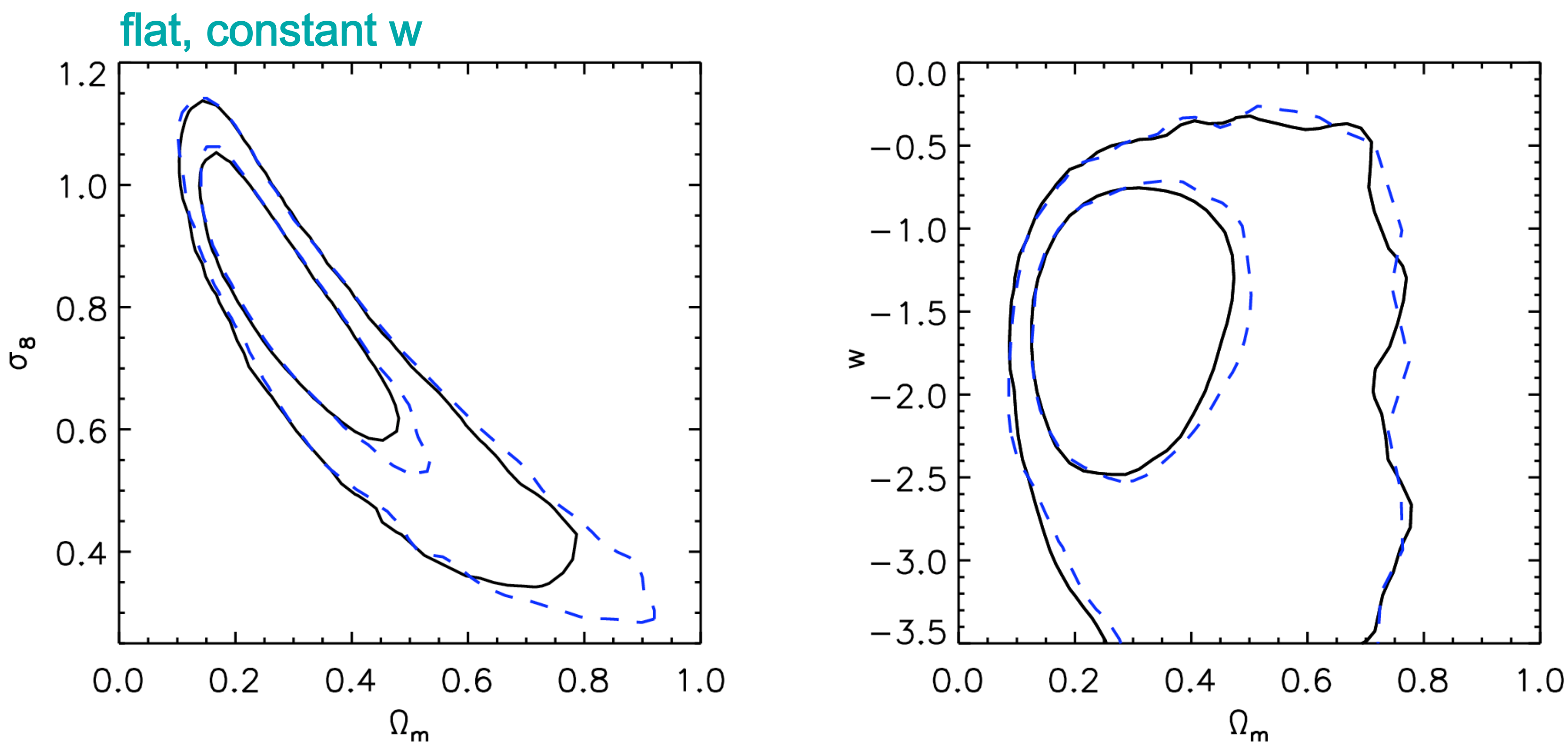
$\Omega_\Lambda = 0.86 \pm 0.21$

(99.99% significance detection, comparable precision to best current SNIa studies combined)

Like SNIa studies, $f_{gas}(z)$ data measure d(z) directly and show Universe is accelerating. Note astrophysics relatively simple and very different from SNIa.

Exploring the sensitivity to priors, scatter and systematic allowances in the XLF analysis

Effects of relaxing the priors (n_s)

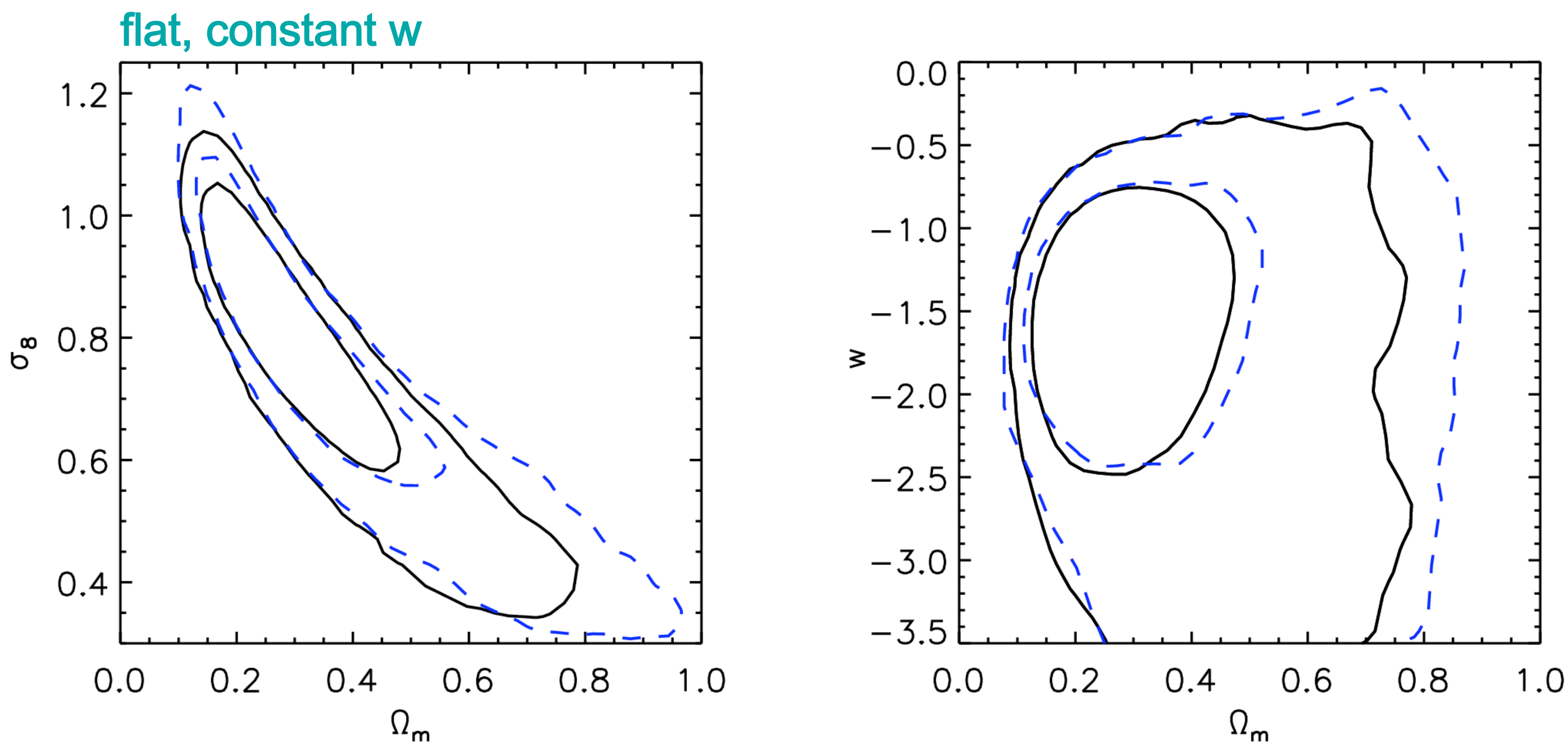


Black solid: standard priors (n_s=0.95)

Blue dash: weak priors (0.9<n_s<1.0)

Conclusions: results relatively insensitive to prior on n_s

Effects of relaxing the priors ($\Omega_b h^2$, h)

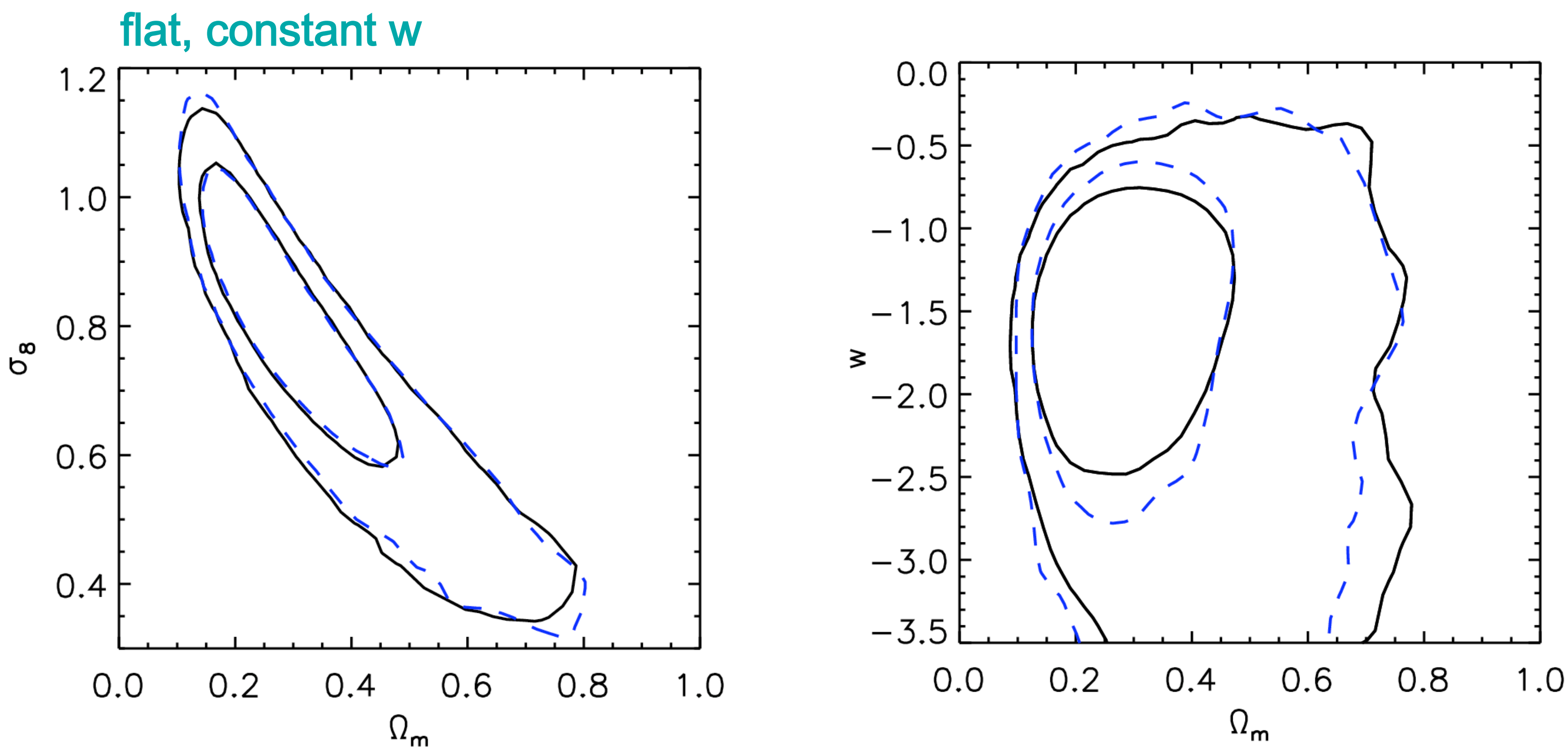


Black solid: standard priors

Blue dash: weak priors (tripple)

Conclusions: results relatively insensitive to priors on $\Omega_b h^2$, h.

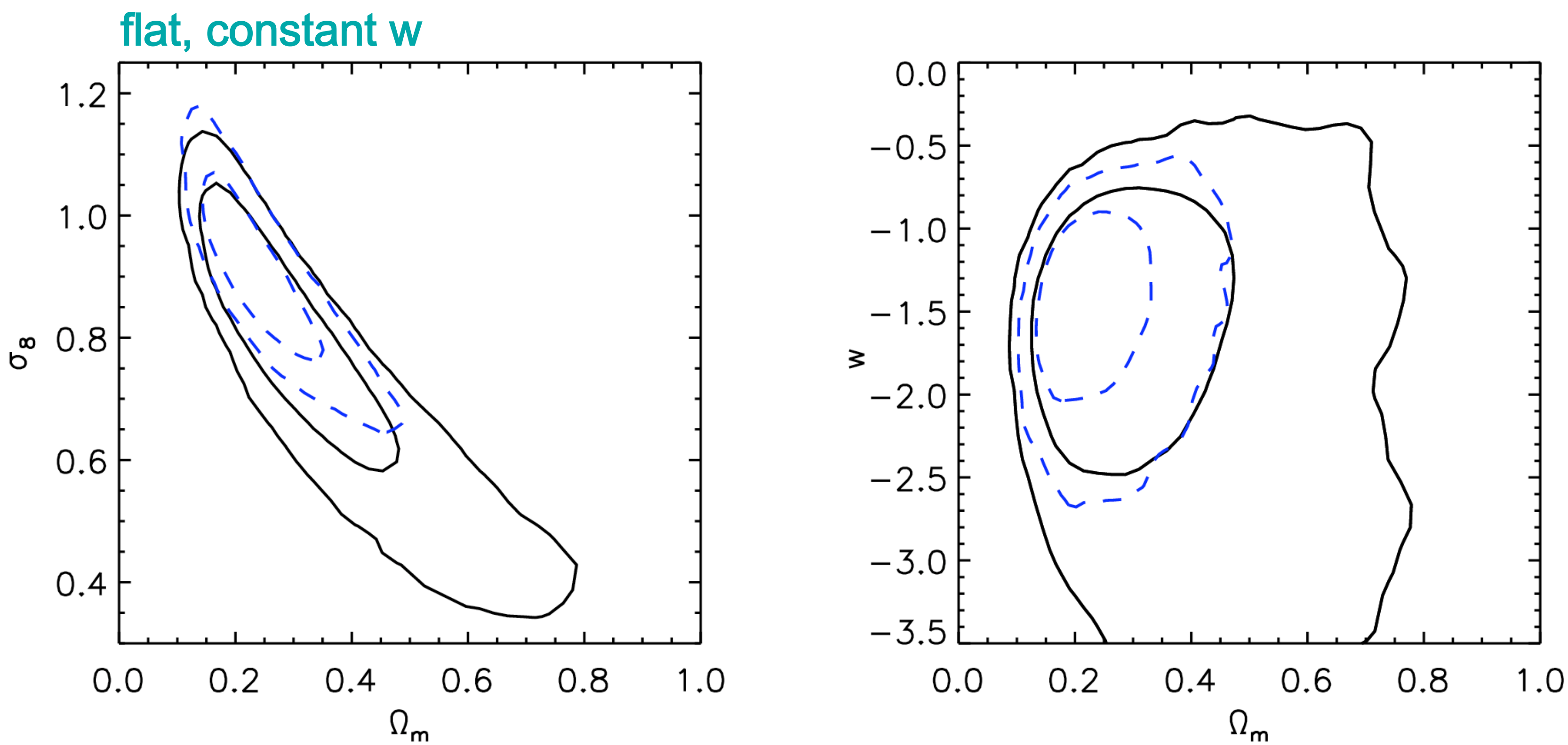
Effects of relaxing the priors (self-similar evolution)



Black solid: standard priors (20%)
Blue dash: weak priors (40%)

Conclusions: results relatively insensitive to prior on γ.

Effects of ignoring scatter (Poisson errors: survey fluxes)

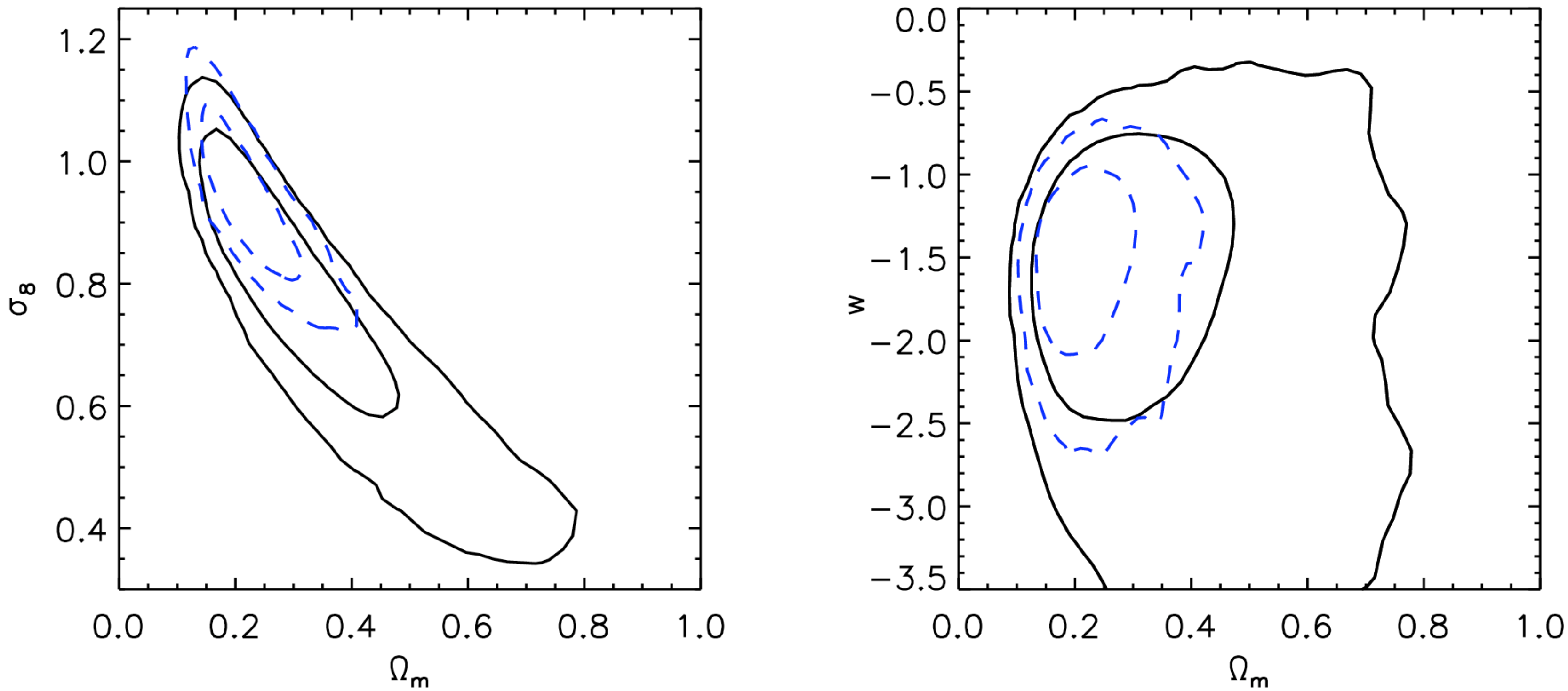


Black solid: standard analysis
Blue dash: ignore Poisson errors

Conclusions: some shift in σ_8, Ω_m
significant underestimation of uncertainties.

Effects of ignoring scatter (intrinsic M-Lx scatter)

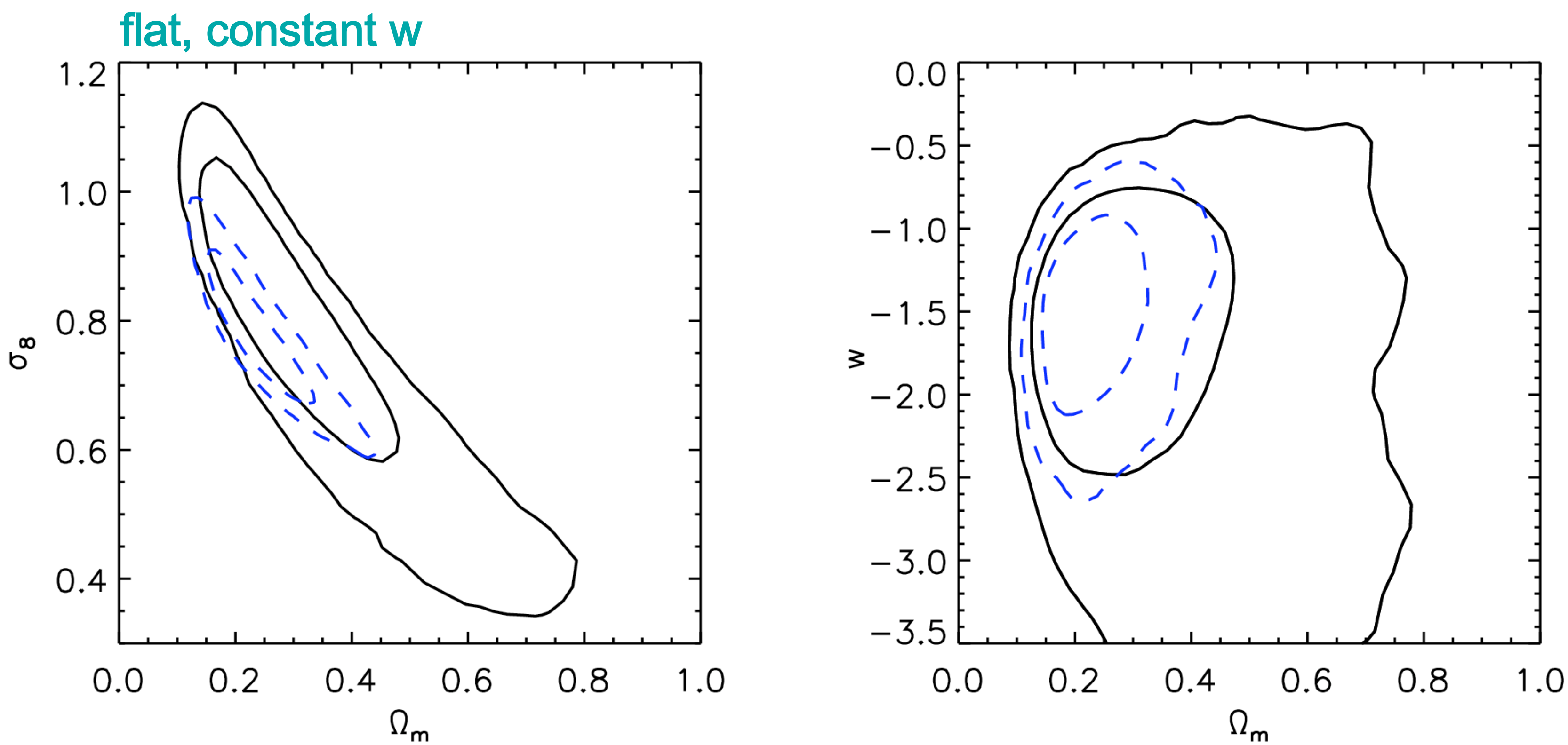
flat, constant w



Black solid: standard analysis
Blue dash: η=0 (zero scatter)

Conclusions: some shift in σ_8, Ω_m
significant underestimation of uncertainties

Correction for non-thermal pressure support



Black solid: standard analysis (25±5% correction)

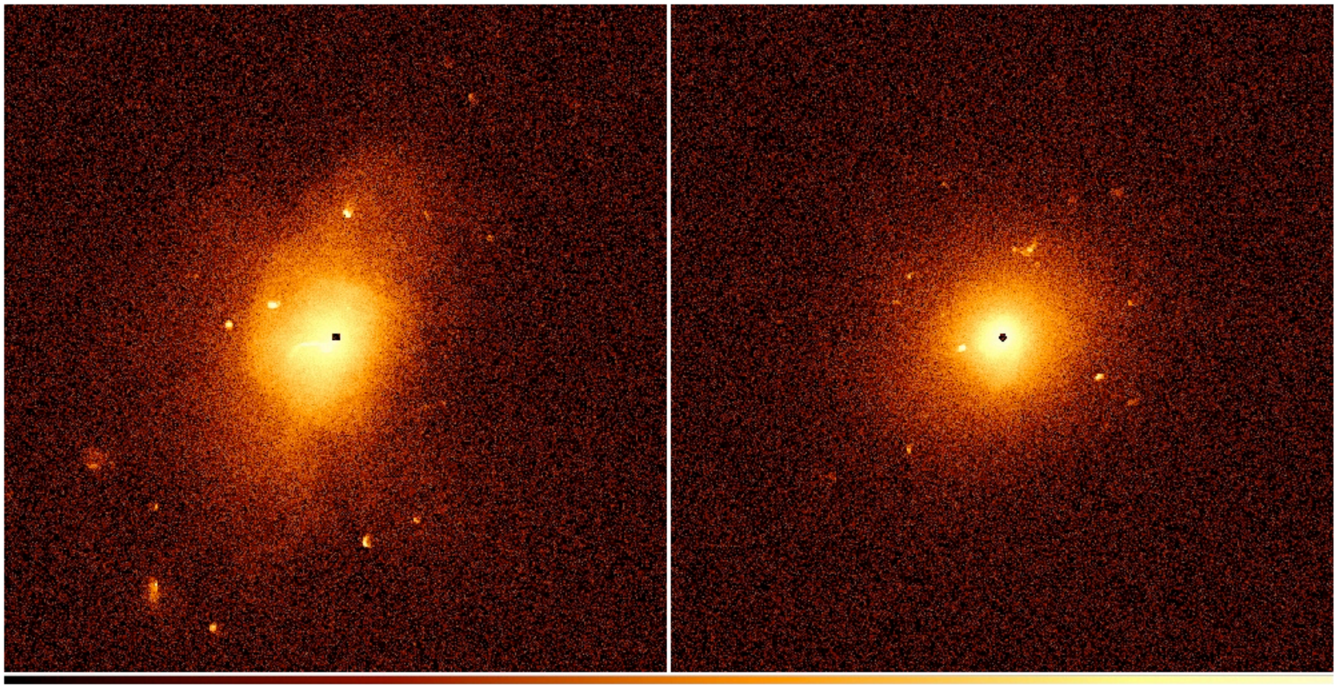
Blue dash: no correction for non-thermal pressure

Conclusions:	significant shift in σ_8 significant underestimation of uncertainties

What do simulations predict?

Hydro simulations of X-ray clusters

Nagai, Vikhlinin & Kravtsov '07

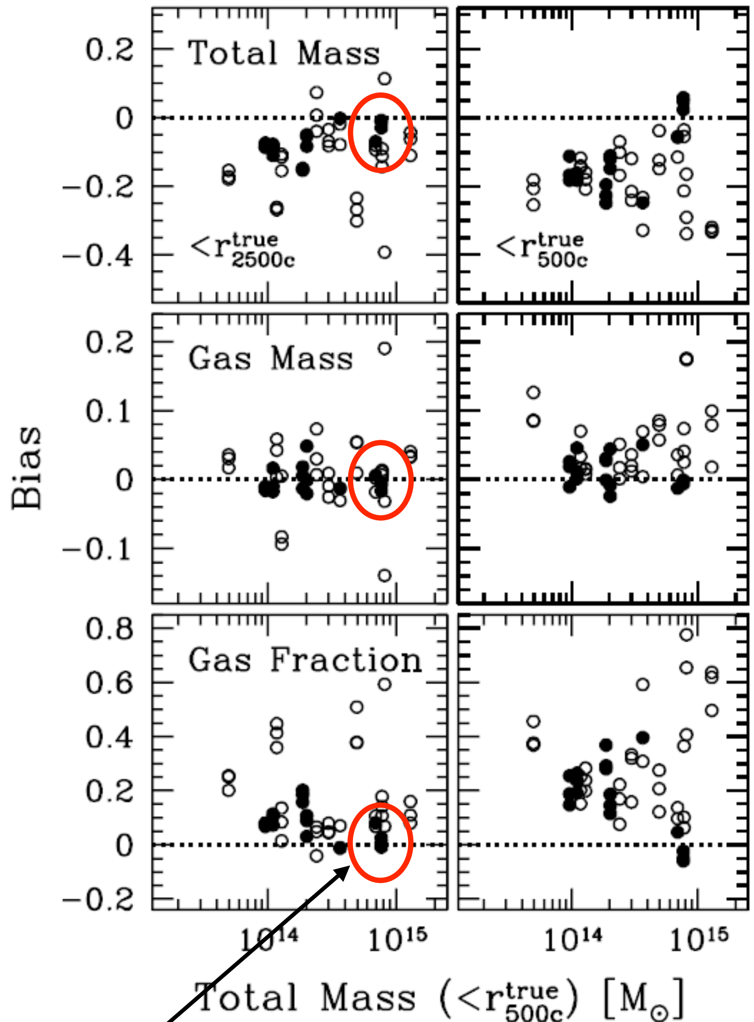


Large, independent programs have been undertaken to simulate X-ray observations of clusters using state-of-the-art hydro codes and selecting/analysing these systems in an identical manner to real observations.

The most recent results have provided good news for X-ray cluster cosmology: systematics are moderate-to-small and can be quantified.

For relaxed clusters, X-ray studies → precise masses

Nagai, Vikhlinin & Kravtsov '07



Relaxed clusters (filled circles)

For largest, relaxed clusters (selected on X-ray morphology) at r_{2500} we expect to measure:

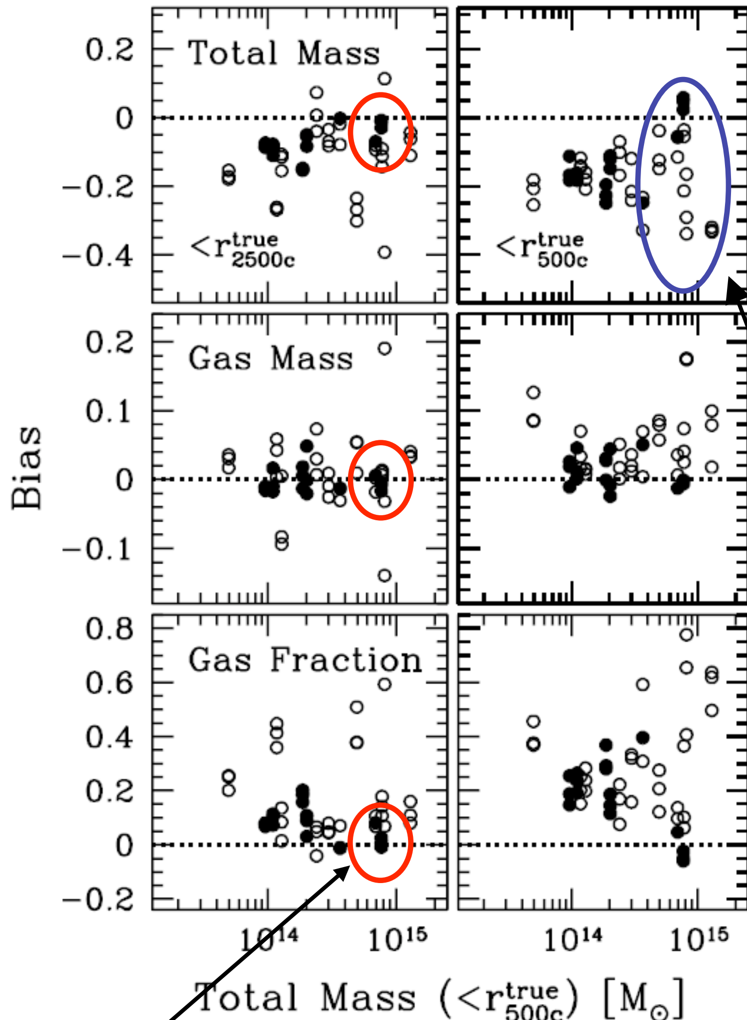
X-ray gas mass to ~1% accuracy.

Total mass and fgas to several % accuracy (both bias and scatter).

Primary uncertainty (beyond innermost core) is residual bulk motions in gas.

For unrelaxed clusters → corrections required

Nagai, Vikhlinin & Kravtsov '07



Relaxed clusters (filled circles)

For largest, relaxed clusters (selected on X-ray morphology) at r_{2500} we expect to measure:

X-ray gas mass to ~1% accuracy.

Total mass to several % accuracy (both bias and scatter).

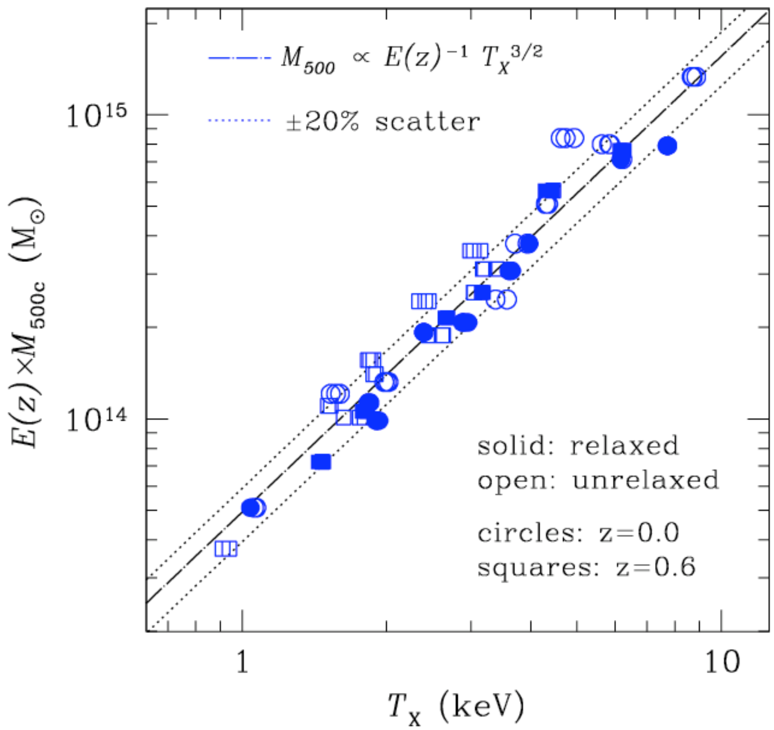
Primary uncertainty (beyond innermost core) is residual bulk motions in gas.

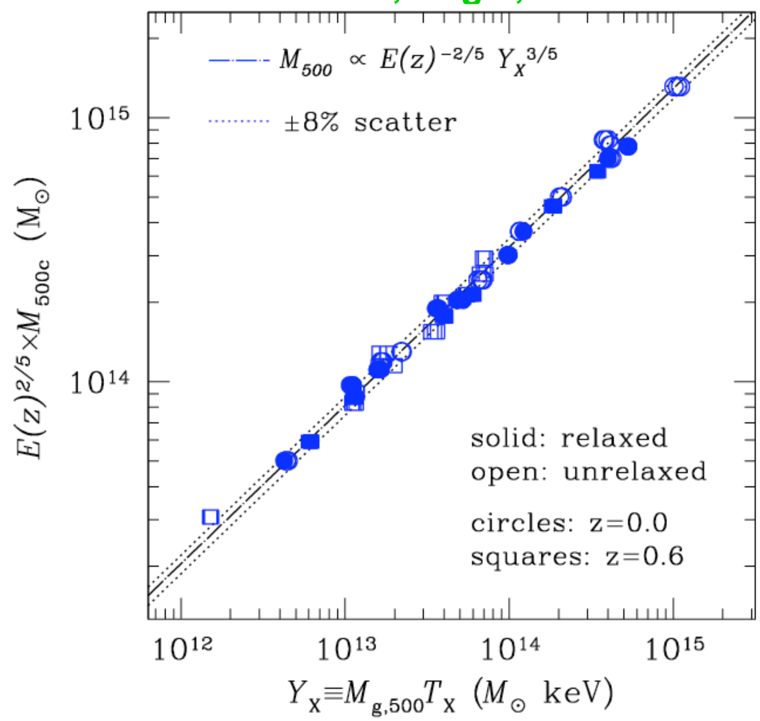
For general cluster population and larger measurement radius (r_{500}):

Corrections of 20-30% to total mass measurements from X-rays required.

X-ray observables correlate tightly with mass

Kravtsov, Nagai, Vikhlinin '06





-The correlations are tight and independent of the background cosmology.

-Good match to observations (at least beyond innermost core)

Current best cluster surveys in X-rays

Low-redshifts ($z<0.3$):

ROSAT Brightest Cluster Sample (BCS: Ebeling et al. '98, '00). Based on RASS (northern sky). 201 clusters with $F_x>4.4\times10^{-12}$ erg cm^{-2} s^{-1} (0.1-2.4keV). 78 massive clusters with $L_x>2.55\times10^{44}h_{70}^{-2}$erg s^{-1}. ~100% complete.

REFLEX (Bohringer et al '04). Based on RASS (southern sky). 447 clusters with $F_x>3.0\times10^{-12}$ erg cm^{-2} s^{-1} (0.1-2.4keV). 130 massive clusters with $L_x>2.55\times10^{44}h_{70}^{-2}$erg s^{-1} and $F_x>3.0\times10^{-12}$ erg cm^{-2} s^{-1}. ~100% complete.

Intermediate redshifts ($0.3<z<0.7$):

MACS (Ebeling et al '01,'07). Based on RASS (whole sky: 23000 sq. deg). 124 clusters with $F_x>10^{-12}$ erg cm^{-2} s^{-1} (0.1-2.4keV). 36 massive clusters with $F_x>2.0\times10^{-12}$ erg cm^{-2} s^{-1} and $L_x>2.55\times10^{44}h_{70}^{-2}$erg s^{-1}. ~100% complete.

*Also note ROSAT 400 sq. degree survey (Vikhlinin et al '08). ROSAT serendipitous cluster catalogue. 266 groups/clusters with $F_x>1.4\times10^{-13}$ erg cm^{-2} s^{-1}.(100% redshift complete).